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CALCULATING PROCEDURE OF SEA-LEVEL STATIC PERFORMANCE OF TWO-SPOOL AFTERBURNING BYPASS JET ENGINE

by

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ABSTRACT:

A calculating procedure is presented for the sea-level static performance of duct burning and afterburning bypass jet engines that have a low pressure and a high pressure spool. Performance values can be determined also for operation without reheat. Influence of temperature and fuel/air ratio on the thermodynamic properties of air and combustion gases is taken into account. A calculating program for a Monroe 1880-43 programmable electronic desk calculator is described which makes it possible to evaluate effects of changes of parameters on performance with minimum effort.

The program will be used to establish the characteristics of compressors required for propulsive units of later generation Navy air-superiority fighter aircraft, to investigate whether the Turbo-Propulsion Laboratory of NPS would be capable of undertaking research and development work of such machines.

Programs of the type presented, and the use of modern programmable desk calculators, will also be of great value for instructional purposes. Teachers can then concentrate on the fundamental nature of particular topics and need not waste time on lengthy derivations, or on simplifications and approximations that are introduced only to solve equations with elementary means. The students would be relieved of the drudgery of routine hand calculations that do not contribute to a better understanding of the subject matter.

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M. H. VAVRA

1. OBJECTIVE

To determine the sea-level static (SLS) performance of a bypass jet engine with or without duct burner and afterburner, and to establish a calculating program for a Monroe Model 1880-43 programmable hand calculator that can be used for optimization and systems analyses.

2. INTRODUCTION

Figure 1 shows a schematic of the engine under consideration with the station identification numbers that will be used in the report.

Total pressures and temperatures at the different stations are denoted by P and T with subscripts corresponding to the indices of the stations. Static pressures are denoted by P_s and static temperatures by T_s.

The total cooling air for the blades ($\dot{w}_{BC}$) and the disks ($\dot{w}_{DC}$) of the high turbine is taken as a fraction ξ of the engine air ($\dot{w}_E$), or

$$\xi = \frac{\dot{w}_{BC} + \dot{w}_{DC}}{\dot{w}_E}$$

The bypass flow rate $\dot{w}_{BP}$ is

$$\dot{w}_{BP} = b\ \dot{w}_E$$

where b is the bypass ratio. After the high turbine, the cooling air $\xi\,\dot{w}_E$, which is supposed to be at the temperature T_3, since the process in the high turbine is considered to be adiabatic, is mixed with the flow rate $(1-\xi)\ \dot{w}_E$ of the high turbine which is at the temperature T_5.

The fuel/air ratio of the main burner is

$$f_B' = \frac{\dot{w}_{fB}}{(1-\xi)\ \dot{w}_E}$$

which is also the fuel/air ratio of the gas passing through the high turbine. After the mixing of cooling air and high turbine flow rate (station 6) the fuel/air ratio is

$$f_B = \frac{\dot{w}_{fB}}{\dot{w}_E} = (1-\xi)\ f_B'$$

which is the fuel/air ratio of the gas flow through the low turbine. The duct burner is taken as part of the afterburner and it is supposed that the bypass flow and the flow leaving the low turbine are heated to the same temperature $T_9 = T_{10}$. The fuel/air ratio necessary to heat $\dot{w}_{BF}$ to T_9 is

$$f_{DB} = \frac{\dot{w}_{fDB}}{\dot{w}_{BP}} = \frac{w_{fDB}}{b\ \dot{w}_E}$$

The fuel flow rate $\dot{w}_{fAB}$ of the afterburner is expressed by

$$f_{AB} = \frac{\dot{w}_{fAB}}{\dot{w}_E}$$

The total fuel/air ratio f_N referred to the total air flow rate

$$\dot{w} = \dot{w}_E + \dot{w}_{BP} = (1+b)\ \dot{w}_E$$

is

$$f_N = \frac{f_B + f_{AB} + b\ f_{DB}}{1 + b} \tag{1}$$

This fuel/air ratio exists at station 11 ahead of the nozzle, and the total nozzle flow rate is

$$\dot{w}_N = (1+f_N)\ \dot{w}$$

The enthalpy of the flow rate $\dot{w}_N$ at station 11 is supposed to be that at the temperature $T_{11} = T_9 = T_{10}$ for the fuel/air ratio f_N. Hence it is assumed that the gas flows through the duct and afterburner are completely mixed at station 11.

The drop in total pressure ΔP through a flow passage is expressed by the pressure drop coefficient

$$\lambda = \frac{\Delta P}{P_{inlet}}$$

where P_{inlet} is the total pressure ahead of the flow passage.

For the inlet nozzle,

$$\lambda_I = \frac{P_0 - P_1}{P_0}$$

For the bypass duct,

$$\lambda_{BP} = \frac{P_2 - P_7}{P_2}$$

For the main burner,

$$\lambda_B = \frac{P_3 - P_4}{P_3}$$

It is assumed that the pressures P_7 and P_8, ahead of duct and afterburner, are equal and that the respective pressure drop coefficients λ_{DB} and λ_{AB} are equal also, or

$$\lambda_{DB} = \lambda_{AB} = \frac{P_7 - P_{11}}{P_7} = \frac{P_8 - P_{11}}{P_8}$$

The pressure P_7 is then

$$P_7 = (1-\lambda_I)\,(1-\lambda_{BP})\,\frac{P_2}{P_1}\;P_0$$

The pressure P_8 equals

$$P_8 = (1-\lambda_I)\,(1-\lambda_B)\,\frac{P_3}{P_1}\,\frac{P_5}{P_4}\,\frac{P_8}{P_5}\,P_0$$

The total compression ratio P_3/P_1 will be chosen, and the pressure P_5/P_4 of the high turbine is obtained from the condition that the high turbine with the inlet temperature T_4 must be capable of driving the high compressor. Hence with $P_8 = P_7$ and $P_6 = P_5$, the pressure ratio P_8/P_5 or P_8/P_6 of the low turbine is

$$\frac{P_8}{P_5} = \frac{P_8}{P_6} = \frac{1 - \lambda_{BP}}{1 - \lambda_B}\;\frac{P_2/P_1}{(P_3/P_1)\,(P_5/P_4)} \tag{2}$$

The pressure ratio P_{12}/P_{11} of the jet nozzle then becomes with $P_{12} = P_0$

$$\frac{P_{12}}{P_{11}} = \frac{P_0}{P_{11}} = \frac{P_0}{P_7\,(1-\lambda_{AB})} = \frac{1}{(1-\lambda_I)\,(1-\lambda_{BP})\,(1-\lambda_{AB})\,(P_2/P_1)} \tag{3}$$

Hence, in addition to P_3/P_1, the pressure ratio P_2/P_1 of the low compressor is also a variable parameter that has to be chosen.

3. THERMODYNAMICS OF REAL GASES

The data of Ref. 1 are used to establish the fuel/air ratios in the burners, and to calculate the enthalpies of air and combustion gases. Reference 1 assumes that the specific heats are functions of temperature and fuel/air ratio only. Even for pressure ratio P_3/P_1 of 30 and higher the effect of pressure on specific heat is indeed negligible.

For a fuel of the composition $(CH_2)_n$, the chemical process for complete combustion is

$$CH_2 + \frac{3}{2}O_2 \rightarrow CO_2 + H_2O$$

With the molecular weights:

$$M_{H_2} = 2.016$$

$$M_{O_2} = 32$$

$$M_C = 12.010$$

there is

$$14.026 \text{ lbm } CH_2 + 48 \text{ lbm } O_2 \rightarrow 44.010 \text{ lbm } CO_2 + 18.016 \text{ lbm } H_2O$$

or, for f pounds of fuel,

$$f \text{ lbm fuel} + 3.422\, f \text{ lbm } O_2 \longrightarrow 3.138\, f \text{ lbm } CO_2 + 1.284\, f \text{ lbm } H_2O$$

Ref. 1. Vanco, M. R. "Computer Program for Design-Point Performance of Turbojet and Turbofan Engine Cycles," NASA TM X-1340, Febr. 1967.

In one pound of air there are:

0.2314 lbm O_2 $(M_{O_2} = 32.0)$

0.7552 lbm N_2 $(M_{N_2} = 28.016)$

0.0129 lbm Argon $(M_{Ar} = 39.944)$

0.0005 lbm CO_2 $(M_{CO_2} = 44.010)$

The combustion products, if f pounds of fuel are burned with one pound of air, have the following composition:

$$\begin{aligned}
\bar{m}_{O_2} &= 0.2314 - 3.422\,f \quad \text{lbm} \\
\bar{m}_{CO_2} &= 0.0005 + 3.138\,f \quad \text{lbm} \\
\bar{m}_{H_2O} &= 1.284\,f \quad \text{lbm} \\
\bar{m}_{N_2} &= 0.7552 \quad \text{lbm} \\
\bar{m}_{Ar} &= 0.0129 \quad \text{lbm} \\
\hline
\bar{m}_{G} &= 1 + f \quad \text{lbm}
\end{aligned}$$

This list shows that the stoichiometric fuel/air ratio, obtained if no oxygen is present in the combustion gases (or $\bar{m}_{O_2} = 0$), equals

$$f_{max} = \frac{0.2314}{3.422} = 0.0675 \frac{\text{lbm fuel}}{\text{lbm air}}$$

The specific heat c_{pG} of the combustion gases per lbm of mixture equals

$$c_{pG} = \frac{\sum \bar{m}_i \; c_{pi}}{1 + f} \tag{4}$$

where i refers to the components listed above. The molecular weight M_G of the combustion gas is obtained from

$$M_G = \frac{1 + f}{\sum \frac{\bar{m}_i}{M_i}}$$

With the mass $\bar{m}_i$ of the components of the above table and their molecular weights M_i

$$M_G = \frac{1 + f}{0.034522 + 0.035648\, f} \tag{5}$$

and

$$R_G = \frac{1545.43}{M_G} \qquad \left(\frac{\text{ft - lb}}{\text{lbm, }^{\circ}\text{R}}\right)$$

Then for air with f = 0,

$$M_G = M_A = 28.9670$$

and

$$R_G = 53.3513 \qquad \left(\frac{\text{ft - lb}}{\text{lbm, }^{\circ}\text{R}}\right)$$

The constituents of the combustion gases have specific heats c_{pi} which can be expressed by

$$c_{pi} = A_i + B_i(10^{-3})\, T + C_i(10^{-6})\, T^2 + D_i(10^{-9})\, T^3 + E_i(10^{-12})\, T^4 \tag{6}$$

Reference 1 gives the coefficients A_i to E_i for the different constituents in accordance with Ref. 2. The specific heat c_{pG} of Eq. 4 can therefore be expressed by a relation of the type

$$c_{pG} = \frac{1}{1 + f}\; F\,(f,\, T) \tag{7}$$

where c_{pG} is in Btu/(lbm, $^{\circ}$R) and T in $^{\circ}$R.

Ref. 2. NASA SP-3001, 1963.

From the first law of thermodynamics

$$dq = T\,ds = du + \frac{p\,dv}{J} = dh - \frac{v\,dp}{J}$$

Further, since

$$dh = c_p\,dT \tag{8}$$

and

$$v = \frac{R_G\,T}{p}$$

there is

$$ds = c_p \frac{dT}{T} - \frac{R_G}{J}\,\frac{dp}{p}$$

For an isentropic process with ds = 0,

$$\frac{R_G}{J}\,\frac{dp}{p} = c_p\,\frac{dT}{T}$$

This equation integrated gives

$$\frac{R_G}{J}\,\ell n\ p = \int_0^T \frac{c_p}{T}\,d\,T = \varphi\ \left(\frac{\text{Btu}}{\text{lbm, }^{\circ}\text{R}}\right) \tag{9}$$

if p = 1 for T = 0.

If an isentropic process takes place from T_i, P_i to P_e, T_e' there is

$$\frac{R_G}{J}\,\ell n\left(\frac{P_e}{P_i}\right) = \int_0^{T_e'} \frac{c_p}{T}\,d\,T - \int_0^{T_i} \frac{c_p}{T}\,d\,T = \varphi_{e'} - \varphi_i \tag{10}$$

and

$$\frac{P_e}{P_i} = e^{\left[\frac{J}{R_G}\left(\varphi_{e'} - \varphi_i\right)\right]} \tag{11}$$

where

$$\frac{J}{R_G} = \frac{J\ M_G}{R_0} = \frac{778.16}{1545.43}\ M_G = 0.5035233\ M_G$$

It is evident that for a given pressure ratio P_e/P_i and an inlet temperature T_i the isentropic temperature T_e' must be found with an iterative process.

Equation 8 integrated gives

$$h = \int_0^T c_p\, d\,T \qquad \left(\frac{\text{Btu}}{\text{lbm Gas}}\right) \tag{12}$$

if h = 0 for T = 0

Turbomachinery calculations are simplified if average values of $\bar{c}_p$ and $\bar{\gamma} = \bar{c}_p/\bar{c}_v$ are introduced, after the inlet and exit conditions have been established with accurate methods. For an isentropic process with known quantities T_i, T_e', P_i, P_e; and h_i, h_e' there exist two ways to determine $\bar{\gamma}$. From

$$h_e' - h_i = \bar{c}_p\ (T_e' - T_i)$$

and

$$\bar{c}_v = \bar{c}_p - R_G/J$$

there is

$$\bar{\gamma} = \bar{\gamma}_1 = \frac{\bar{c}_p}{\bar{c}_v} = \frac{1}{1 - \dfrac{R_G}{J}\dfrac{T_e' - T_i}{h_e' - h_i}}$$

From Eq. 10, however, with

$$\frac{R_G}{J} \ln\left(\frac{P_e}{P_i}\right) = \bar{c}_p\ \ell n\left(\frac{T_e'}{T_i}\right) = \varphi_{e'} - \varphi_i$$

$$\bar{\gamma} = \bar{\gamma}_2 = \frac{1}{1 - \frac{R_G}{J} \frac{\ln(T_e'/T_i)}{\varphi_{e'} - \varphi_i}}$$

Experience has shown that the value $\bar{\gamma}_2$ gives closer correspondance with real gas data than $\bar{\gamma}_1$. However, to determine the local value of $\gamma = \gamma_\ell$ at a given static temperature T_s and fuel/air ratio f, it is necessary to apply the same method as for $\bar{\gamma}_1$, or

$$\gamma_\ell = \frac{1}{1 - \frac{R_G}{J} \frac{T_s}{h_s}}$$

The velocity of sound "a" at the temperature T_s then becomes

$$a = \sqrt{\gamma_\ell \; g \; R_G \; T_s} = \sqrt{\frac{g \; R_G \; T_s}{1 - \frac{R_G}{J} \frac{T_s}{h_s}}}$$

where h_s is the enthalpy that corresponds to the static temperature T_s.

In Ref. 1 the integrals of Eqs. 9 and 12 have been calculated. A total of ten constants appears in the results, namely,

$C_1 = 0.24062$

$C_2 = 0.017724 \; (10^{-3})$

$C_3 = 0.038056 \; (10^{-6})$

$C_4 = 0.012662 \; (10^{-9})$

$C_5 = 0.0013012 \; (10^{-12})$

$D_1 = 0.22091$

$D_2 = 0.51822 \; (10^{-3})$

$D_3 = 0.19462 \; (10^{-6})$

$D_4 = 0.045089 \; (10^{-9})$

$$D_5 = 0.0043275 \ (10^{-12})$$

Then,

$$\varphi = \frac{1}{1+f}\left[C_1 \ \ln T - C_2 \ T + \frac{C_3}{2} T^2 - \frac{C_4}{3} T^3 + \frac{C_5}{4} T^4\right]$$

$$+ \frac{1}{1+f}\left[D_1 \ \ln T + D_2 \ T - \frac{D_3}{2} T^2 + \frac{D_4}{3} T^3 - \frac{D_5}{4} T^4\right] \quad (13)$$

and

$$h = \frac{1}{1+f} \ h_A + \frac{f}{1+f} \ h_G \qquad \left(\frac{\text{Btu}}{\text{lbm Gas}}\right) \quad (14)$$

where h_A is due to the air, and h_G due to the combustion gases of the mixture. Then

$$h_A = \left[C_1 \ T - \frac{C_2}{2} T^2 + \frac{C_3}{3} T^3 - \frac{C_4}{4} T^4 + \frac{C_5}{5} T^5\right] \quad (15)$$

$$h_G = \left[D_1 \ T + \frac{D_2}{2} T^2 - \frac{D_3}{3} T^3 + \frac{D_4}{4} T^4 - \frac{D_5}{5} T^5\right] \quad (16)$$

The quantities h and φ are shown in Figs. 6 and 7 as functions of T and f.

4. FUEL/AIR RATIO OF COMBUSTOR

Figure 2 shows a combustion chamber were $\dot{w}_i$ (lbm/s) of air with a fuel/air ratio f_i enter the combustor at the temperature T_i. To be determined is the fuel flow rate $\dot{w}_f$ necessary to heat this mixture to the temperature T_e. The fuel enters the combustor at the temperature T_f and it is supposed that the combustor efficiency is η, or that η(LHV) Btu's are released per lbm of fuel during combustion, where (LHV) is the lower heating value of the fuel in Btu/lbm.

A heat balance gives

$$\dot{w}_i(1 + f_i) \ h_i + \dot{w}_f \ h_f + \dot{w}_f \ \eta(\text{LHV}) = \left[\dot{w}_i(1 + f_i) + \dot{w}_f\right] h_e$$

With

$$\dot{w}_f = \Delta f \ \dot{w}_i$$

$$f_e = f_i + \Delta f$$

and Eq. 14,

$$h_{Ai} + f_i\, h_{Gi} + \Delta f\, h_f + \Delta f\, \eta(LHV) = h_{Ae} + (f_i + \Delta f)\, h_{Ge}$$

or

$$\Delta f \left[h_f + \eta(LHV) - h_{Ge} \right] = h_{Ae} - h_{Ai} + f_i (h_{Ge} - h_{Gi})$$

and

$$\Delta f = \frac{\dot{w}_f}{\dot{w}_i} = \frac{h_{Ae} - h_{Ai} + f_i(h_{Ge} - h_{Gi})}{h_f + \eta(LHV) - h_{Ge}}$$

All enthalpies are zero at $T = 0^{\circ}$ R.

For JP-4 fuel the lower heating value is 18,400 Btu/lbm, and its specific heat is about 0.5. Hence at a chosen fuel temperature of 520° R, or $h_f = 260$ Btu/lbm, there is

$$\Delta f = \frac{h_{Ae} - h_{Ai} + f_i(h_{Ge} - h_{Gi})}{\eta(18{,}400) + 260 - h_{Ge}} \tag{17}$$

with h_A and h_G from Eqs. 15 and 16. With $f_e = f_i + \Delta f$ the enthalpy h_e is obtained from Eq. 14.

Equation 17 can be used for all three combustors. For the main burner there are:

$$T_i = T_3$$

$$f_i = 0$$

$$T_e = T_4$$

$$\eta = \eta_B$$

$$\Delta f = f_e = f_B'$$

For the after-burner:

$$T_i = T_8$$

$$f_i = f_B = (1 - \xi)\, f_B'$$

$$T_e = T_{10}$$

$$\eta = \eta_{AB}$$

$$\Delta f = f_{AB}$$

$$f_e = f_B + f_{AB}$$

For the duct burner:

$$T_i = T_2$$

$$f_i = 0$$

$$T_e = T_9 = T_{10}$$

$$\eta = \eta_{AB}$$

$$\Delta f = f_e = f_{DB}$$

The fuel/air ratios $f_B + f_{AB}$, and/or f_{DB}, have to be lower than the stoichiometric ratio $f_{max} = 0.0675$.

5. MIXING OF FLOWS AT CONSTANT PRESSURE

The process illustrated in Fig. 3 will be used to evaluate the conditions that occur after the high turbine, were the cooling air is mixed with the turbine discharge, and those where the bypass and the engine flow mix before entering the jet nozzle. With the symbols of Fig. 4, on assuming an adiabatic process,

$$\dot{w}_i(1 + f_i)\, h_i + \dot{w}_{ii}(1 + f_{ii})\, h_{ii} = \left[\dot{w}_i(1 + f_i) + \dot{w}_{ii}(1 + f_{ii})\right] h_e$$

Let

$$\dot{w}_e = \dot{w}_i + \dot{w}_{ii} = (1 + \zeta)\, \dot{w}_i$$

or

$$\zeta = \frac{\dot{w}_{ii}}{\dot{w}_i} \tag{18}$$

Then

$$h_e = \frac{(1 + f_i)\, h_i + \zeta(1 + f_{ii})\, h_{ii}}{1 + \zeta + f_i + \zeta\, f_{ii}} \tag{19}$$

and

$$f_e = \frac{f_i + \zeta\, f_{ii}}{1 + \zeta} \tag{20}$$

With Eq. 14, there is from Eq. 19,

$$h_e = \frac{h_{Ai} + f_i\, h_{Gi} + \zeta\, h_{Aii} + \zeta\, f_{ii}\, h_{Gii}}{(1 + \zeta) + f_i + \zeta\, f_{ii}}$$

For the known values of h_e and f_e the temperature T_e is obtained by iterating Eq. 14.

For the mixing ahead of the jet nozzle, there is $T_i = T_{ii}$, or $h_{Ai} = h_{Aii}$, and $h_{Gi} = h_{Gii}$. Then, with Eq. 20

$$h_e = \frac{(1 + \zeta)h_{Ai} + h_{Gi}(f_i + \zeta\, f_{ii})}{(1 + \zeta) + f_i + \zeta\, f_{ii}} = \frac{h_{Ai} + fe\, h_{Gi}}{1 + fe}$$

However

$$h_e = \frac{1}{1 + fe}\, h_{Ae} + \frac{fe}{1 + fe}\, h_{Ge}$$

Hence, as could be expected, there must be

$$h_{Ae} = h_{A1} \text{ and } h_{Ge} = h_{Gi}$$

and the temperature after the mixing process is equal to $T_i = T_{ii}$. Hence h_e can be calculated directly for $T_i = T_{ii}$ and the fuel/air ratio f_e of Eq. 20.

For the mixing process after the high turbine there are:

$$\zeta = \xi/(1 - \xi)$$

$$T_i = T_5$$

$$f_i = f_B'$$

$$T_{ii} = T_3$$

$$f_{ii} = 0$$

$$f_e = f_B$$

For the mixing process ahead of the jet nozzle:

$$\zeta = b$$

$$T_i = T_{ii} = T_9 = T_{10}$$

$$f_i = f_B + f_{AB}$$

$$f_{ii} = f_{DB}$$

$$f_e = f_N$$

6. LOW AND HIGH COMPRESSOR CALCULATIONS

Figure 5 represents a compression process in an entropy diagram. The pressure ratio P_e/P_i of both low and high compressor will be chosen. Then

$$\Delta h_{is} = h_e' - h_i$$

and the specific work necessary to drive the compressor is, with the compressor efficiency η_c,

$$\Delta h_w = \frac{\Delta h_{is}}{\eta_c}.$$

From Eq. 10

$$\varphi_e' = \varphi_i + \frac{R_G}{J} \ln\left(\frac{P_e}{P_i}\right)$$

where both values of φ are for f = 0. From φ_{T2}, the temperature T_e' is obtained by an iteration. Then, from Eq. 15

$$h_e' = h_A(T_e')$$

Also

$$h_i = h_A(T_i)$$

Further

$$h_e = h_i + \frac{h_e' - h_i}{\eta_c}$$

From h_e, the temperature T_e is obtained with an iteration of Eq. 15 for $f = 0$.

The driving power of the compressor is

$$HP = \dot{w}_c(h_e - h_i)\,\frac{J}{550}$$

For the low compressor:

$$\dot{w}_c = \dot{w}_E(1 + b) = \dot{w}$$

$$h_e = h_2$$

$$h_i = h_1$$

$$\eta_c = \eta_{LC}$$

For the high compressor:

$$\dot{w}_c = \dot{w}_E = \dot{w}/(1 + b)$$

$$h_e = h_3$$

$$h_i = h_2$$

$$\eta_c = \eta_{HC}$$

7. HIGH TURBINE CALCULATIONS

The high turbine must drive the high compressor. Hence,

$$(1 - \xi)\,\dot{w}_E\,(1 + f_B')(h_4 - h_5) = \dot{w}_E(h_3 - h_2)$$

or

$$h_5 = h_4 - \frac{h_3 - h_2}{(1 - \xi)(1 + f_B')} \tag{21}$$

where the value of f, to calculate h_5 and h_4, equals f_B'. Equation 14 iterated yields T_5. With the high turbine efficiency η_{HT}, the isentropic enthalpy h_5' at the high turbine exit is

$$h_5' = h_4 - \frac{h_4 - h_5}{\eta_{HT}} \tag{22}$$

This value of h_5' is used to determine the corresponding isentropic temperature T_5'. Then by Eq. 11

$$\frac{P_5}{P_4} = e^{\left[\frac{J}{R_G}\left(\varphi_{5'} - \varphi_4\right)\right]} \tag{23}$$

The values of φ and R_G must be determined for $f = f_B'$.

8. EXPANSION PROCESS

The pressure ratio in the low turbine is known from Eq. 2, if P_5/P_4 has been determined. The pressure ratio in the jet nozzle is given by Eq. 3. For both processes the same calculating method can be applied; for the low turbine to establish its work output, and for the jet nozzle to determine the discharge velocity V_d.

Let P_i, T_i be the inlet and P_e, T_e the discharge conditions. The temperature T_e' occurs for an isentropic expansion from P_i, T_i to P_e. The gas shall have the fuel/air ratio f. Then, by Eq. 10

$$\varphi_{e'} = \varphi_i + \frac{R_G}{J} \ln\left(\frac{P_e}{P_i}\right)$$

where the values of φ and R_G depend on f. The value of $\varphi_{e'}$ is used to obtain T_e'. For T_e' the enthalpy h_e' is determined from Eq. 14. Then, with the efficiency η_e of the expansion process,

$$h_e = h_i - (h_i - h_e')\,\eta_e$$

From h_e there is obtained the exit temperature T_e.

9. LOW TURBINE CALCULATIONS

The method of section 7 can be used for the low turbine with:

$$T_i = T_6$$

$$P_e/P_i = P_8/P_5 \qquad \text{(Eq. 2)}$$

$$f = f_B$$

$$\eta_e = \eta_{LT}$$

to determine $T_e = T_8$ and $h_e = h_8$. The low turbine power is then

$$HP_{LT} = \dot{w}_E(1 + f_B)(h_6 - h_8)\,\frac{J}{550}$$

Since the low turbine drives the low compressor, there is

$$\dot{w}_E(h_6 - h_8) = \dot{w}(h_2 - h_1) = \dot{w}_E(1 + b)(h_2 - h_1)$$

Hence the bypass ratio b equals

$$b = \frac{(1 + f_B)(h_6 - h_8)}{h_2 - h_1} - 1$$

10. JET NOZZLE DISCHARGE VELOCITY

The method of section 7 can be used to establish the jet nozzle discharge conditions with:

$$T_i = T_9 = T_{10} = T_{11}$$

$$P_e/P_i = P_o/P_{11} = P_{12}/P_{11} \qquad \text{(Eq. 3)}$$

$$f = f_N \qquad \text{(Eq. 11)}$$

$$\eta_e = \Psi^2$$

where Ψ is the velocity coefficient of the nozzle. The static temperature T_{12} and the static pressure P_{12} are equal to T_e and P_e of section 7. The static enthalpy h_{12} corresponds to h_e, and

$$V_d = \sqrt{2\ g\ J(h_{11} - h_{12})}$$

The Mach number M_d of V_d equals (see section 3)

$$M_d = \frac{V_d}{\sqrt{\dfrac{g\ R_G\ T_{12}}{1 - \dfrac{R_G}{J}\dfrac{T_{12}}{h_{12}}}}}$$

11. ENGINE PERFORMANCE

The thrust F produced at sea-level static conditions is

$$F = \dot{w}(1 + f_N)\ \frac{V_d}{g} \qquad \text{(lbf)}$$

or the so-called specific impulse I_{SP} becomes

$$I_{SP} = \frac{F}{\dot{w}} = \frac{(1 + f_N)\ V_d}{g} \qquad \left(\frac{\text{lbf}}{\text{lbm/s}}\right) \tag{24}$$

The specific fuel consumption is

$$SFC = \frac{f_N\ \dot{w}}{F} = \frac{f_N(3600)}{I_{SP}} \qquad \left(\frac{\text{lb fuel/hr}}{\text{lb thrust}}\right)$$

12. ENGINE THRUST VS. OUTER DIAMETER OF LOW COMPRESSOR

The calculating program contains an auxiliary part which can be used to determine the engine thrust for a specified outer diameter D_{T1} of the low compressor if it has so-called impulse bladings.

With a chosen hub/tip ratio ahead of the first stage; $r_{h1} = D_{h1}/D_{T1}$, and from the velocity diagram of Fig. 4, or

$$V_1 = U_T \cot \beta_{1T}$$

there is

$$\dot{w} = \frac{\pi}{4} D_{T1}{}^2(1 - r_{h1}{}^2)\ U_T \cot \beta_{1T}\ \frac{P_{s1}}{R_G\ T_{s1}}\ k_1 \tag{25}$$

where k_1 is a blockage factor to account for the displacement thickness of the wall boundary layers at station 1.

Equation 25 holds for the assumption that the axial velocity V_1 at the low compressor inlet eye area is constant and that it can be calculated from the conditions at the tip diameter where the peripheral speed U_T (ft/s) and the relative flow angle β_{1T} exist. The quantities T_{s1} and P_{s1} are static temperature and pressure, respectively, at station 1 of Fig. 1. The total temperature at 1 equals T_o, or $h_1 = h_0$, and

$$P_1 = (1 - \lambda_I)\ P_o$$

Then

$$h_{s1} = h_o - \frac{V_1^{\ 2}}{2g\ J} = h_o - \frac{(U_T \cot \beta_{1T})^2}{2g\ J}$$

This equation is similar to Eq. 21. It is possible, therefore, to use the high turbine calculating procedure to establish the static temperature T_{s1} and the static pressure P_{si}. With

$$(h_4 - h_5) = \frac{(U_T \cot \beta_{1T})^2}{2g\ J}$$

and

$$\eta_{HT} = 1$$

this procedure gives $T_{s1} = (T_e)$; and $P_{s1}/P_1 = (P_e/P_i)$ for $f = 0$. The values in the brackets shall indicate that their equality pertains only to the correspondence of the values that are obtained from the calculation; to avoid misinterpretation, for instance, that T_{s1} has the same magnitude as the total temperature T_e.

Then

$$P_{s1} = (P_{s1}/P_1)\ P_1 = (P_{s1}/P_1)(1 - \lambda_I)\ P_0$$

where P_o must be introduced in psia, if D_{T1} is in inches, to obtain $\dot{w}$ of

Eq. 25 in lbm/s.

The thrust F of the engine is then with Eq. 24,

$$F = \dot{w}\ I_{SP} \qquad \text{(lbf)}$$

Hence the quantities that must be chosen to obtain $\dot{w}$ and F are D_{T1}, r_{h1}, U_T, β_{1T} and k_1, in addition to P_o, T_o.

Of interest is also the Mach number M_{W1} of the relative inlet velocity W_{1T} of Fig. 4 at the tip of the rotor blade. From section 3

$$M_{W1} = \frac{W_{1T}}{a_{s1}} = \frac{U_T/\sin\ \beta_{1T}}{a_{s1}} = \frac{U_T/\sin\ \beta_{1T}}{\sqrt{\dfrac{g\ R_G\ T_{s1}}{1 - \dfrac{R_G}{J}\dfrac{T_{s1}}{h_{s1}}}}}$$

Evidently these relations hold only if the first stage of the low compressor is of the impulse type, where a rotor with axial absolute inlet velocity is followed by a stator.

13. CALCULATION PROCEDURE

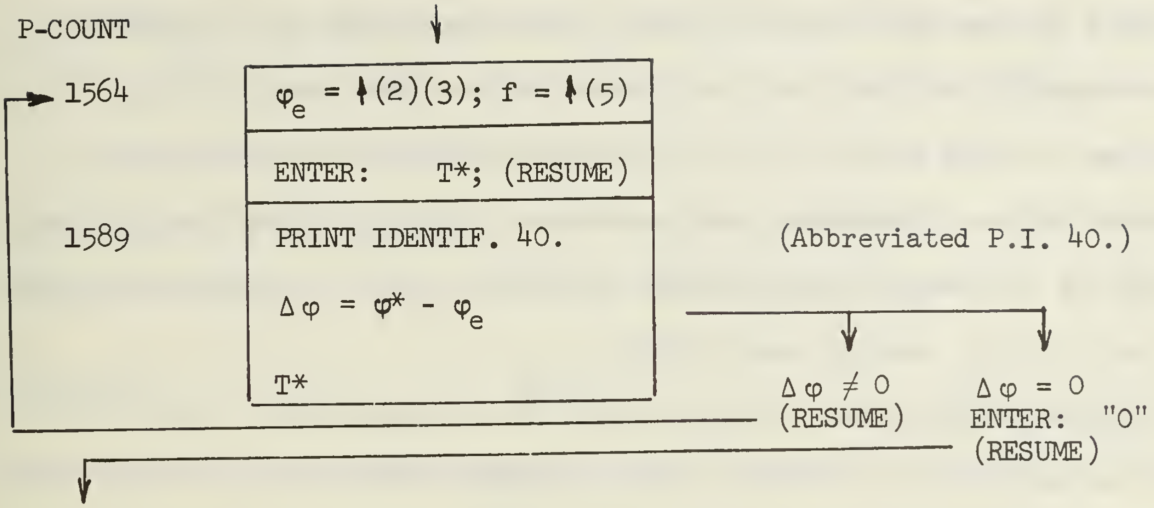
Programs VA 513 is used to introduce constants and the parameters of the jet engine in the manner listed in the operating instructions of Appendix A. The entered data are printed for checking purposes. Then program VA 514 is read into the calculator. This program calculates the conditions of state at all stations of Fig. 1, and prints the particulars of the different elements of the unit. Subsequently, the overall performance parameters of the engine are printed out, namely, the specific impulse, the specific fuel consumption, the bypass ratio, and the Mach number of the flow at the discharge of the jet nozzle. These quantities are independent of the geometry and the blading particulars of the low compressor at station 1 of Fig. 1.

The program can then process an arbitrary number of sets of low compressor inlet data; that is, diameter, hub/tip ratio, peripheral rotor speed, and relative tip flow angle of the first stage of the low compressor, to obtain a particular thrust of the jet engine. For these calculations it is assumed that this first stage is of the impulse type as described in section 12. For specified inlet conditions the program prints out the particulars of the turbomachines.

The necessary steps that have to be undertaken by the operator are listed in Appendix A. They consist primarily in trial- and error methods to establish the temperatures at the different stations of the cycle.

These methods of successive approximations are explained in the following. Let the inlet conditions of an element of the jet engine; that is, of either a compressor or a turbine, be identified by the subscript i, and its discharge conditions by the subscript e (see Fig. 5 for compression process). A similar symbolism will be adopted for the mixing process of Fig. 3, with the difference that the subscripts i and ii are used for the inlet properties of the two gas flows that are mixed. For known inlet conditions the program establishes either the enthalpy h_e of Eq. 14 or the function φ_e of Eq. 14 at the discharge of an element, and the operator must determine the temperature T_e that corresponds to either h_e or φ_e. For given values of h_e or φ_e, the corresponding temperature T_e is also a function of the fuel/air ratio f. For known values of h_e or φ_e, and f, a first approximation of $T_e = T^*$ can be obtained from Figs. 6a, 6b or Figs. 7a, 7b, respectively. If $T^* = T_e$ is entered, the program calculates either $\Delta h = h^* - h_e$, or $\Delta\varphi = \varphi^* - \varphi_e$, where h^* and φ^* are the values of h and φ for T^* and f. Then the quantities Δh, or $\Delta\varphi$, and T^* are printed out, after a print identification number which is left-justified.

In the operating instructions all iterations are indicated by the set-up which is shown below.



In this example the temperature T_e must be established at P-Count 1564 for particular values φ_e and f. The symbol $\uparrow(2)(3)$ indicates that φ_e is stored in data register 32, and $\uparrow(5)$ shows that f is stored in scratch pad register 5. These values can be recalled and printed. Then, a first approximation of $T_e = T^*$ is obtained from Fig. 7 which is entered at P-Count 1564. After depressing the (RESUME) key the calculator will stop at P-Count 1589 to display the print identifier (40.), the difference $\Delta\varphi = \varphi^* - \varphi_e$, and the value of T* which was entered at P-Count 1564. The quantity φ^* in $\Delta\varphi$ is the value of φ that corresponds to T* and f, whereas φ_e is the value for which T_e has to be determined. If the error $\Delta\varphi$ is excessive, the (RESUME) key must be depressed to return the calculations to P-Count 1564, where a better approximation for $T^* = T_e$ can be entered, namely, smaller values if $\Delta\varphi$ was negative. This process is repeated as often as necessary until the error $\Delta\varphi$ has been reduced to acceptable values. Then a zero (0) must be entered on the keyboard before the (RESUME) key is depressed. With this manipulation the program leaves the iteration loop and continues with the subsequent calculations.

Iterations of T_e for know values of h_e and f follow the same pattern, with the exception that $\Delta h = h^* - h_e$ is displayed instead of $\Delta\varphi$. If it is assumed that the temperatures T_e to be determined deviate by not more

$\pm$ 0.005 $^{\circ}R$ from their correct values, the error $\Delta\varphi$ should not exceed about $3(10^{-6})$, and the error Δh should be less than about $2(10^{-3})$. The program sets the decimal point to six, hence all print-outs have six decimal digits. Therefore, the iterations of T_e for φ_e must be continued until $\Delta\varphi$ is smaller than 0.000003, and those of T_e for h_e must be repeated until Δh is smaller than 0.00200.

During the execution of the program the so-called print-outs A occur for the compressors, turbines, and the exhaust nozzle and inlet duct. The form of print-out A is as follows:

Identifier (left-justified, negative number in red)

P_e/P_i = exit pressure/inlet pressure

T_i = inlet temperature ($^{\circ}R$)

h_i = inlet enthalpy (Btu/lbm)

η = efficiency of process

T_e = exit temperature ($^{\circ}R$)

h_e = exit enthalpy (Btu/lbm)

$h_e - h_i$ or $h_i - h_e$ (positive value)

f = fuel/air ratio

$\bar{\gamma}$ = average value of $\gamma = c_p/c_v$ for isentropic process from P_i, T_i to P_e

R_G = gas constant $\left(\frac{\text{ft - lb}}{\text{lbm, }^{\circ}\text{R}}\right)$

For the turbomachines the values of P_e, P_i, T_i, h_i, T_e, h_e correspond to the total conditions at inlet and exit. For the exhaust nozzle and the inlet duct the pressure P_e, the temperature T_e and the enthalpy h_e pertain to the static conditions at the exit, and $h_i - h_e$ equals the kinetic energy

$V_e^2/2gJ$ where V_e is the actual velocity at the exit of the exhaust nozzle N at station 12 of Fig. 1; or ahead of the blading of the low compressor at station 1 of Fig. 1 for the inlet duct I.

The identifier preceding print-out A is indicative of the element to which the results pertain. In the following table this correspondence is listed.

Identifier	Element	Inlet and Exit Stations of Fig. 1 (i) - (e)
- 101.	Inlet Nozzle	0 - 1
- 12.	Low Compressor	1 - 2
- 23.	High Compressor	2 - 3
- 45.	High Turbine	4 - 5
- 68.	Low Turbine	6 - 8
- 1,112.	Exhaust Nozzle	11 - 12

The results of the combustion processes are given with the so-called print-outs B, which have the following form:

Identifier (left-justified, negative number in red)

T_e = exit temperature (^oR)

h_e = exit enthalpy (Btu/lbm)

Δf = fuel added in combustor per pound of mixture

f_e = fuel/air ratio at exit of combustor.

The so-called print-out C displays the result of a mixing process as follows:

Identifier (left-justified, negative number in red)

T_e = temperature after mixing (^oR)

h_e = enthalpy after mixing (Btu/lbm)

$\zeta = \dot{w}_{ii}/\dot{w}_i$ = ratio of flow rates of gases to be mixed

f_e = fuel/air ratio after mixing

In print-outs B and C the identifier has the form -7xx, where xx is indicative of the index of the exit station, in accordance with Fig. 1, of either the combustor, or the station where the mixing has occured. Thus, the identifier -704. refers to the conditions at station 4 after the main burner, and -711 is indicative of station 11 of Fig. 1 after the gas flows from the duct and afterburner have been mixed.

Identifiers and/or print-outs that do not correspond to the above-mentioned categories are explained in Appendix A.

The program can be used also for jet engines without reheat by duct burner and afterburner. Appendix B gives the operating instructions for such units.

The complete listing of the calculating steps of programs VA 513 and VA 514 is given in Appendix C together with forms that show the contents of the scratch pad and main data registers.

14. EXAMPLES

Two examples are given which can be used to check the program. Example A deals with a jet engine with afterburner which may be classified as a second generation unit for the propulsion of air-superiority aircraft of the F-14 type. It operates with turbine inlet temperatures of 2900 $^{\circ}$R (2540 $^{\circ}$F) and has an overall pressure ratio P_3/P_1 of 30. Its diameter at the low compressor inlet is 36 inches, equal to that of the F401 engine presently in development for the F-14B aircraft (see Ref. 3).

Tables I(1) and I(2) give the results of the calculations. These tables are of standard form to which the print-outs of the program are attached. Table I(2) shows that the thrust of the unit can be increased from 28,563 pound to 32,618 pound by increasing the tip speed of the rotor

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Ref. 3 Aviation Week & Space Technology, Vol. 96, No. 26, June 26, 1972, pp. 88/97.

of the first stage of the low compressor from 1600 ft/s to 1700 ft/s, and by decreasing its hub/tip ratio from 0.4 to 0.35. However the higher tip speed increases the tip Mach number of the relative flow of the first compressor stage from about 1.65 to 1.91. The bypass ratio is b = 0.88 for both cases.

The following list gives the temperatures which were determined by the iterations in Example A to make possible a quick check of the program on the Monroe calculator. Indicated are the P-Counts, in the same order as they occur in the calculating sequence, and the errors, in either $\Delta\varphi$ or Δh.

P-Count	ENTRY: T*	PRINT-OUT:
1213	$T_2' = 742.015$	$\Delta\varphi = 0.000\ 000$
1272	$T_2 = 777.813$	$\Delta h = -0.000\ 013$
1213	$T_3' = 1397.775$	$\Delta\varphi = 0.000\ 000$
1272	$T_3 = 1479.194$	$\Delta h = 0.000\ 020$
1567	$T_5 = 2295.791$	$\Delta h = -0.000\ 079$
1628	$T_5' = 2203.423$	$\Delta h = 0.000\ 016$
1933	$T_6 = 2258.783$	$\Delta h = -0.000\ 092$
1361	$T_8' = 1818.390$	$\Delta\varphi = 0.000\ 000$
1419(*)	$T_8 = 1863.262$	$\Delta h = 0.000\ 003$
1361	$T_{12}' = 2655.945$	$\Delta\varphi = 0.000\ 000$
1419	$T_{12} = 2700.647$	$\Delta h = 0.000\ 027$

For data (1) of Table I(1) of the first-stage rotor of the low compressor, the obtained temperatures are:

P-Count	ENTRY: T*	PRINT-OUT:
1567	$T_1 = 473.629$	$\Delta h = -0.000\,056$

For data (2) of Table I(1)

1567	$T_1 = 439.692$	$\Delta h = 0.000\,033.$

Example B deals with the same engine as Example A but without reheat by duct and afterburner. These elements are supposed to be installed however so that their pressure drops are taken into account. Tables II(1) and II(2) give the results of the calculations. With data (1) of the first-stage of the low compressor, the thrust is 17,309 pounds, and with data (2) it becomes 19,766 pound. Hence, reheat to 3400 $^{\circ}$R (2940 $^{\circ}$F) increases the thrust by about 11,200 to 12,800 pound, but the specific fuel consumption is increased from 0.676 lb fuel/(lb thrust, hour) to a value of 1.691.

To check out Example B on the calculator without iterations, the same temperatures must be introduced as given in the preceding list for Example A, up to and including P-Count 1419 that is marked with an asterisk (iteration of T_8). The subsequent entries are:

P-Count	ENTRY: T*	PRINT-OUT:
1933	$T_{11} = 1387.086$	$\Delta h = -0.000\,014$
1361	$T_{12}' = 1020.635$	$\Delta \varphi = 0.000\,000$
1419	$T_{12} = 1042.728$	$\Delta h = -0.000\,059$

For data (1) and (2) of the first-stage rotor of the low compressor of Table II(1), the temperatures to be introduced at P-Count 1567 are $T_1 = 473.629$ and $T_1 = 439.692$, respectively, as for Example A.

TABLE I(1) JET ENGINE (WITH) ~~(WITHOUT)~~ AFTERBURNER ; PROG. VA 513/514

CONFIGURATION EXAMPLE A FORM 1 of 2;

INPUT DATA (GENERAL)

	-100.
P_0	14.7000
T_0	520.0000
P_2/P_1	3.5000
P_3/P_1	30.0000
T_4	2,900.0000
T_9-T_{10}	3,400.0000
ξ	0.0500
λ_I	0.0100
λ_{BP}	0.0200
λ_B	0.0500
λ_{AB}	0.0600
η_{LC}	0.8600
η_{HC}	0.8800
η_{HT}	0.8700
η_{LT}	0.9000
η_B	0.9600
η_{AB}	0.9300
ψ	0.9700

CALCULATED PERFORMANCE DATA

	-200.
I_{SP}	109.976328
SFC	1.691403
b	0.880183
M_d	1.355328

CHOSEN DATA OF FIRST-STAGE ROTOR OF LOW COMPRESSOR

	(1) INLET DUCT	(2) INLET DUCT
	-101.	-101.
P_{s1}/P_1	0.721370	0.556480
T_1	520.000000	520.000000
h_1	124.288220	124.288220
η	1.000000	1.000000
T_{s1}	473.629000	439.692000
h_{s1}	113.171386	105.049657
h_1-h_{s1}	11.116834	19.238563
f	0.000000	0.000000
$\bar{\gamma}$	1.400536	1.400972
R_G	53.351334	53.351334

	ENGINE DATA (1)	ENGINE DATA (2)
	-300.	-300.
D_{T1}	36.000000	36.000000
r_{h1}	0.400000	0.350000
U_T	1,600.000000	1,700.000000
β_{1T}	65.000000	60.000000
k_1	0.980000	0.980000
F	28,563.00000	32,618.00000
$\dot{w}$	259.728519	296.595808
HP_{LC}	22,927.00000	26,182.00000
HP_{HC}	34,710.00000	39,637.00000
M_{W1}	1.653353	1.907981

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TABLE I(2) JET ENGINE DATA (WITH) (~~WITHOUT~~) AFTERBURNER ; PROG. VA 513/514.
CONFIGURATION EXAMPLE A FORM 2 of 2;

LOW COMPRESSOR

	-12.
P_2/P_1	3.500000
T_1	520.000000
h_1	124.288220
η_{LC}	0.860000
T_2	777.813000
h_2	186.680747
h_2-h_1	62.392527
f	0.000000
$\bar{\gamma}$	1.396268
R_G	53.351334

HIGH COMPRESSOR

	-23.
P_3/P_2	8.571429
T_2	777.813000
h_2	186.680734
η_{HC}	0.880000
T_3	1,479.194000
h_3	364.277862
h_3-h_2	177.597128
f	0.000000
$\bar{\gamma}$	1.375188
R_G	53.351334

EXIT MAIN BURNER

	-704.
T_4	2,900.000000
h_4	788.603825
Δf	0.024763
f_4	0.024763

HIGH TURBINE

	-45.
P_5/P_4	0.299998
T_4	2,900.000000
h_4	788.603825
η_{HT}	0.870000
T_5	2,295.791000
h_5	606.176939
h_4-h_5	182.426886
f	0.024763
$\bar{\gamma}$	1.295604
R_G	53.393384

INLET LOW TURBINE

	-706.
T_6	2,258.783000
h_6	594.359904
$\zeta=\xi/(1-\xi)$	0.052632
f_6	0.023525

LOW TURBINE

	-68.
P_8/P_6	0.401172
T_6	2,258.783000
h_6	594.359812
η_{LT}	0.900000
T_8	1,863.262000
h_8	479.746692
h_6-h_8	114.613120
f	0.023525
$\bar{\gamma}$	1.311382
R_G	53.391330

EXIT AFTERBURNER

	-710.
T_{10}	3,400.000000
h_{10}	982.361522
Δf	0.031388
f_{10}	0.054913

EXIT DUCT BURNER

	-709.
T_9	3,400.000000
h_9	973.588906
Δf	0.047987
f_9	0.047987

INLET JET NOZZLE

	-711.
T_{11}	3,400.000000
h_{11}	978.269121
b	0.880183
f_{11}	0.051671

EXPANSION JET NOZZLE

	-1,112.
P_{12}/P_{11}	0.313287
T_{11}	3,400.000000
h_{11}	978.269121
$\eta_N - \psi^2$	0.940900
T_{12}	2,700.647000
h_{12}	752.197995
$h_{11}-h_{12}$	226.071126
f	0.051671
$\bar{\gamma}$	1.270314
R_G	53.436831

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TABLE II(1) JET ENGINE (~~WITH~~) (WITHOUT) AFTERBURNER ; PROG. VA 513/514

CONFIGURATION EXAMPLE B FORM 1 of 2;

INPUT DATA (GENERAL)

	-100.
P_0	14.7000
T_0	520.0000
P_2/P_1	3.5000
P_3/P_1	30.0000
T_4	2,900.0000
T_9-T_{10}	0.0000
ξ	0.0500
λ_I	0.0100
λ_{BP}	0.0200
λ_B	0.0500
λ_{AB}	0.0600
η_{LC}	0.8600
η_{HC}	0.8800
η_{HT}	0.8700
η_{LT}	0.9000
η_B	0.9600
η_{AB}	1.0000
$\dot{\psi}$	0.9700

CALCULATED PERFORMANCE DATA

	-200.
I_{SP}	66.645600
SFC	0.675865
b	0.880183
M_d	1.342137

CHOSEN DATA OF FIRST-STAGE ROTOR OF LOW COMPRESSOR

	(1) INLET DUCT	(2) INLET DUCT
	-101.	-101.
P_{s1}/P_1	0.721370	0.556480
T_1	520.000000	520.000000
h_1	124.288220	124.288220
η	1.000000	1.000000
T_{s1}	473.629000	439.692000
h_{s1}	113.171386	105.049657
h_1-h_{s1}	11.116834	19.238563
f	0.000000	0.000000
$\bar{\gamma}$	1.400536	1.400972
R_G	53.351334	53.351334

	ENGINE DATA (1)	ENGINE DATA (2)
	-300.	-300.
D_{T1}	36.000000	36.000000
r_{h1}	0.400000	0.350000
U_T	1,600.000000	1,700.000000
β_{1T}	65.000000	60.000000
k_1	0.980000	0.980000
F	17,309.00000	19,766.00000
$\dot{w}$	259.728519	296.595808
HP_{LC}	22,927.00000	26,182.00000
HP_{HC}	34,710.00000	39,637.00000
M_{W1}	1.653353	1.907981

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TABLE II(2) JET ENGINE DATA (~~WITH~~) (WITHOUT) AFTERBURNER ; PROG. VA 513/514.
CONFIGURATION EXAMPLE B FORM 2 of 2;

LOW COMPRESSOR

	-12.
P_2/P_1	3.500000
T_1	520.000000
h_1	124.288220
η_{LC}	0.860000
T_2	777.813000
h_2	186.680747
h_2-h_1	62.392527
f	0.000000
$\bar{Y}$	1.396268
R_G	53.351334

HIGH COMPRESSOR

	-23.
P_3/P_2	8.571429
T_2	777.813000
h_2	186.680734
η_{HC}	0.880000
T_3	1,479.194000
h_3	364.277862
h_3-h_2	177.597128
f	0.000000
$\bar{Y}$	1.375188
R_G	53.351334

EXIT MAIN BURNER

	-704.
T_4	2,900.000000
h_4	788.603825
Δf	0.024763
f_4	0.024763

HIGH TURBINE

	-45.
P_5/P_4	0.299998
T_4	2,900.000000
h_4	788.603825
η_{HT}	0.870000
T_5	2,295.791000
h_5	606.176939
h_4-h_5	182.426886
f	0.024763
$\bar{Y}$	1.295604
R_G	53.393384

INLET LOW TURBINE

	-706.
T_6	2,258.783000
h_6	594.359904
$\zeta=\xi/(1-\xi)$	0.052632
f_6	0.023525

LOW TURBINE

	-68.
P_8/P_6	0.401172
T_6	2,258.783000
h_6	594.359812
η_{LT}	0.900000
T_8	1,863.262000
h_8	479.746692
h_6-h_8	114.613120
f	0.023525
$\bar{Y}$	1.311382
R_G	53.391330

EXIT AFTERBURNER

	-710.
T_{10}	1,863.262000
h_{10}	479.746695
Δf	0.000000
f_{10}	0.023525

EXIT DUCT BURNER

	-709.
T_9	777.813000
h_9	186.680734
Δf	0.000000
f_9	0.000000

INLET JET NOZZLE

	-711.
T_{11}	1,387.086000
h_{11}	344.247063
b	0.880183
f_{11}	0.012512

EXPANSION JET NOZZLE

	-1,112.
P_{12}/P_{11}	0.313287
T_{11}	1,387.086000
h_{11}	344.247049
$\eta_N=\psi^2$	0.940900
T_{12}	1,042.728000
h_{12}	254.679907
$h_{11}-h_{12}$	89.567142
f	0.012512
$\bar{Y}$	1.359289
R_G	53.372837

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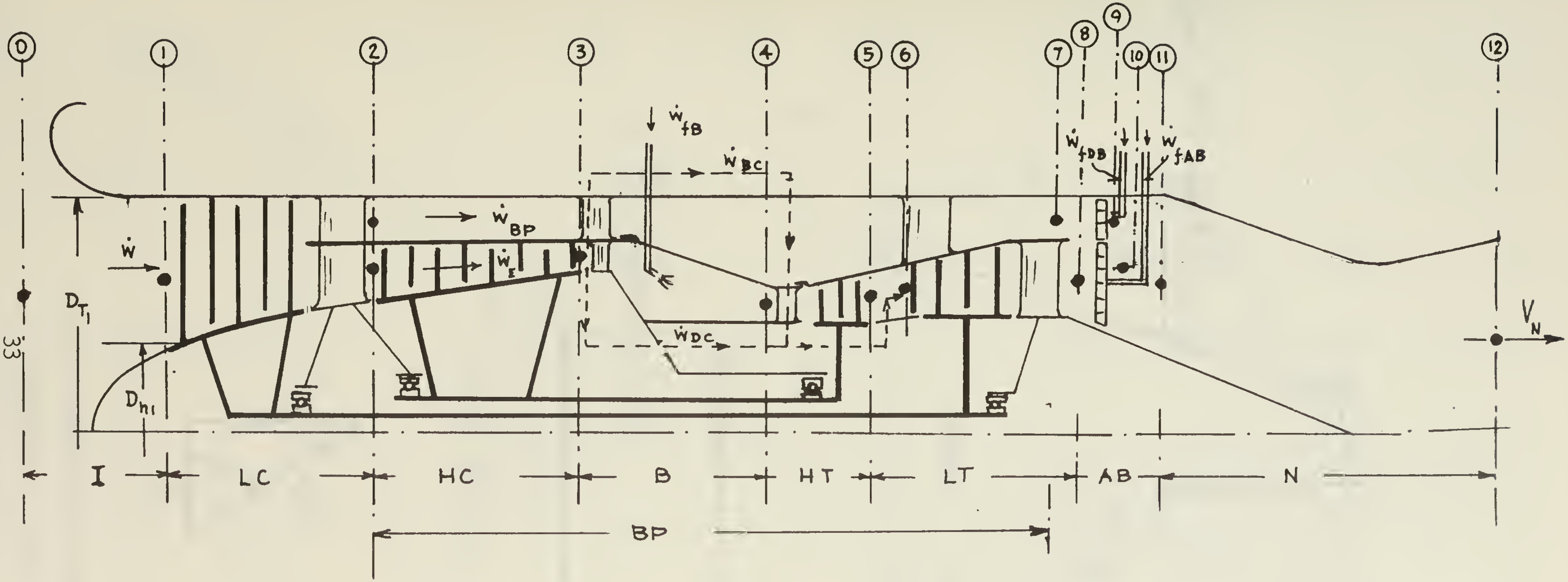


FIG. 1 SCHEMATIC OF BYPASS JET ENGINE WITH DUCT AND AFTERBURNER

I = Inlet Nozzle for Sea Level Static Tests

N = Jet Nozzle with Complete Expansion to $P_0 = P_{12}$

BP = Bypass Duct

B = Main Burner

AB = Duct and Afterburner

LC = Low Compressor ; HC = High Compressor

LT = Low Turbine ; HT = High Turbine

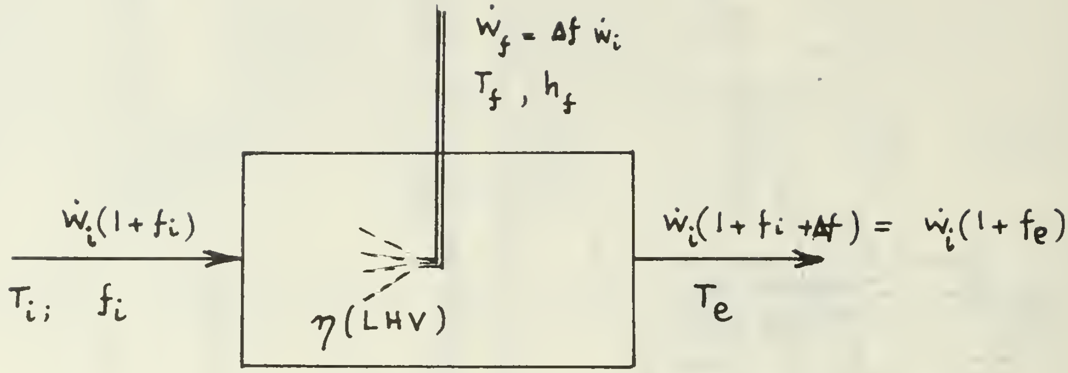


FIG. 2 COMBUSTOR

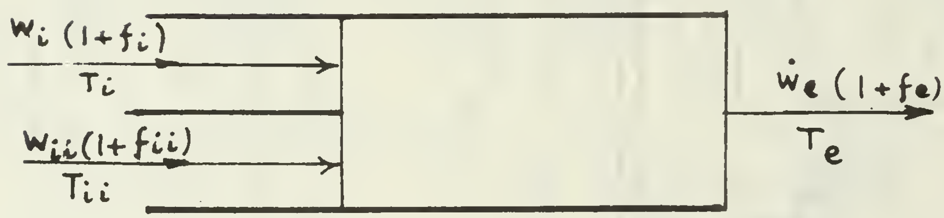


FIG. 3 MIXING PROCESS

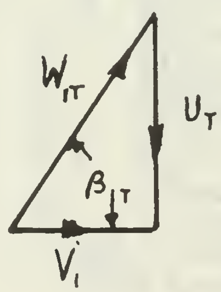


FIG. 4 VELOCITY DIAGRAM AT TIP

OF LOW COMPRESSOR

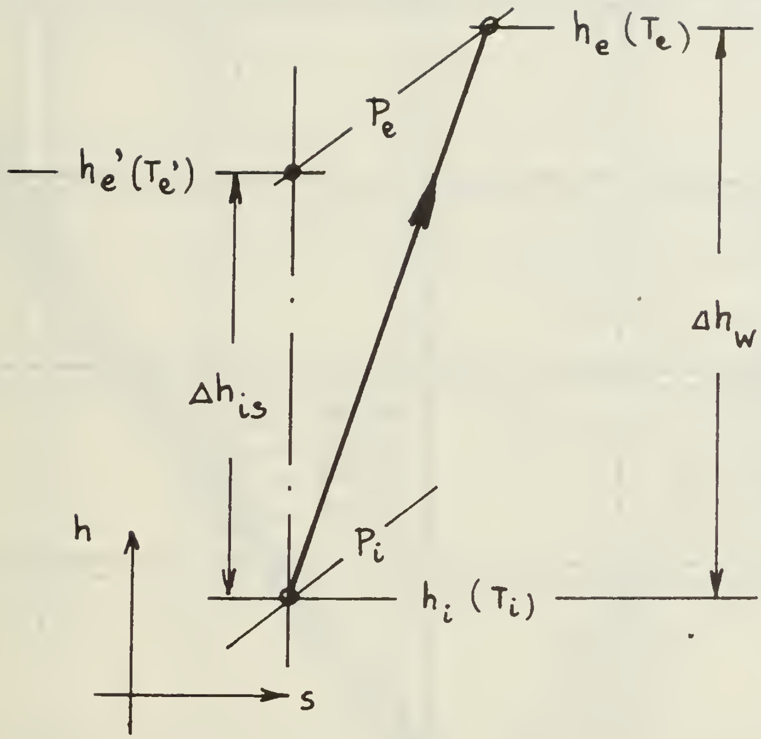
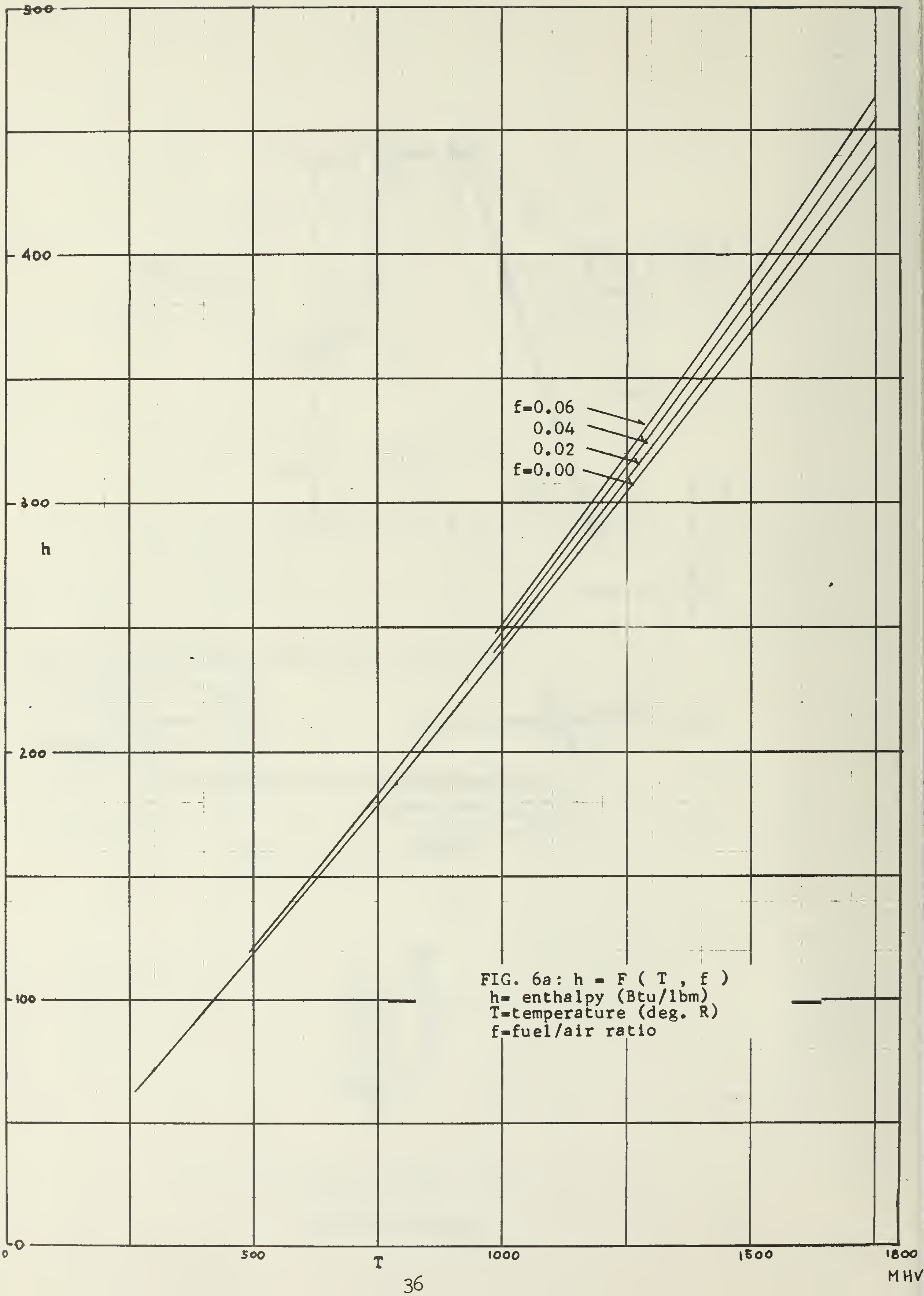
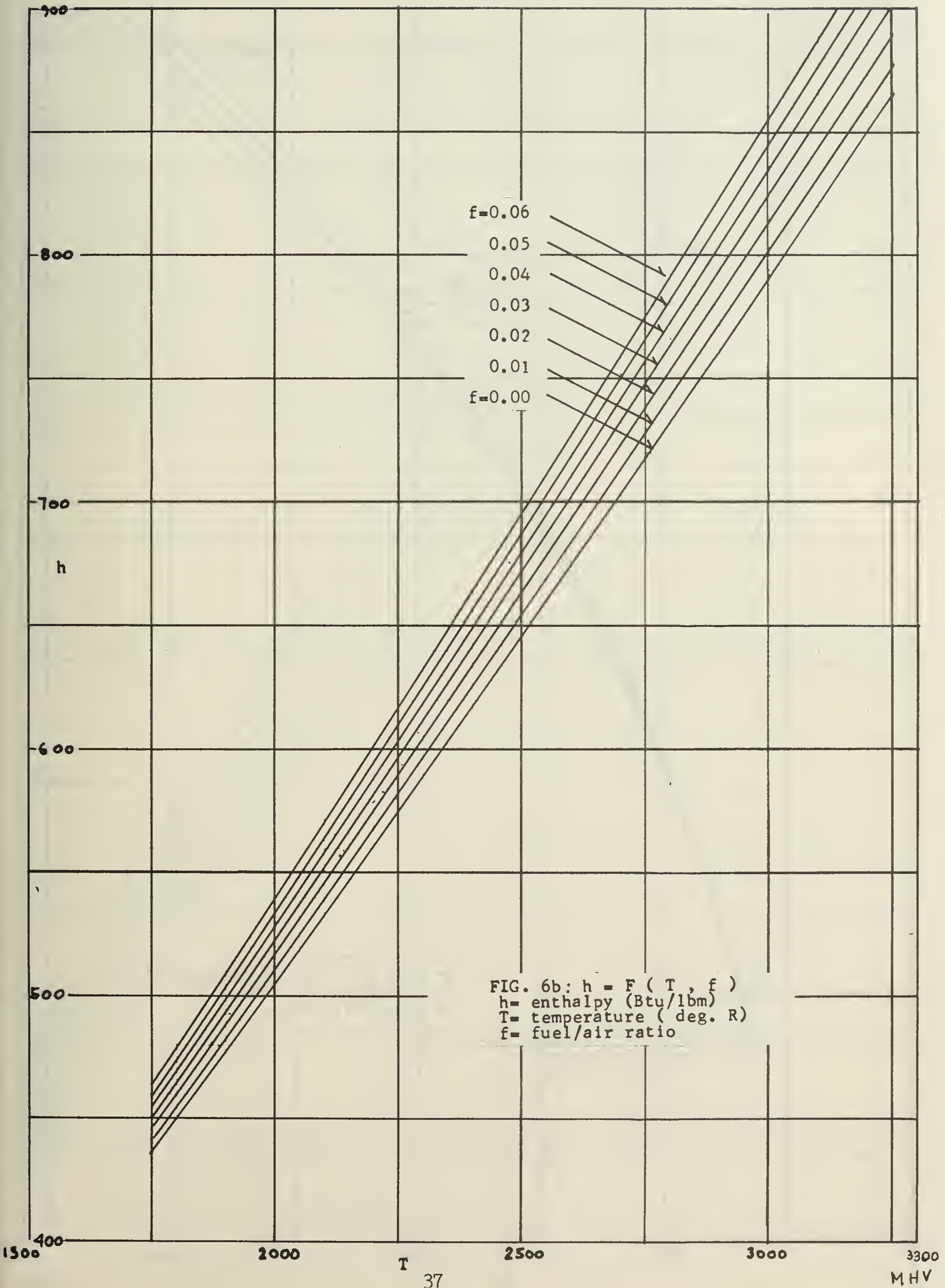


FIG. 5 COMPRESSOR PROCESS

h = total enthalpy
T = total temperature
P = total pressure


f=0.06
0.04
0.02
f=0.00
FIG. 6a: h = F (T , f)
h= enthalpy (Btu/lbm)
T=temperature (deg. R)
f=fuel/air ratio
500
400
300
200
100
0
h
0
500
1000
1500
1800
T
MHV


900
800
700
h
600
500
400
1500
2000
2500
3000
3300
T
f=0.06
0.05
0.04
0.03
0.02
0.01
f=0.00
FIG. 6b: h = F (T , f)
h= enthalpy (Btu/lbm)
T= temperature (deg. R)
f= fuel/air ratio
MHV

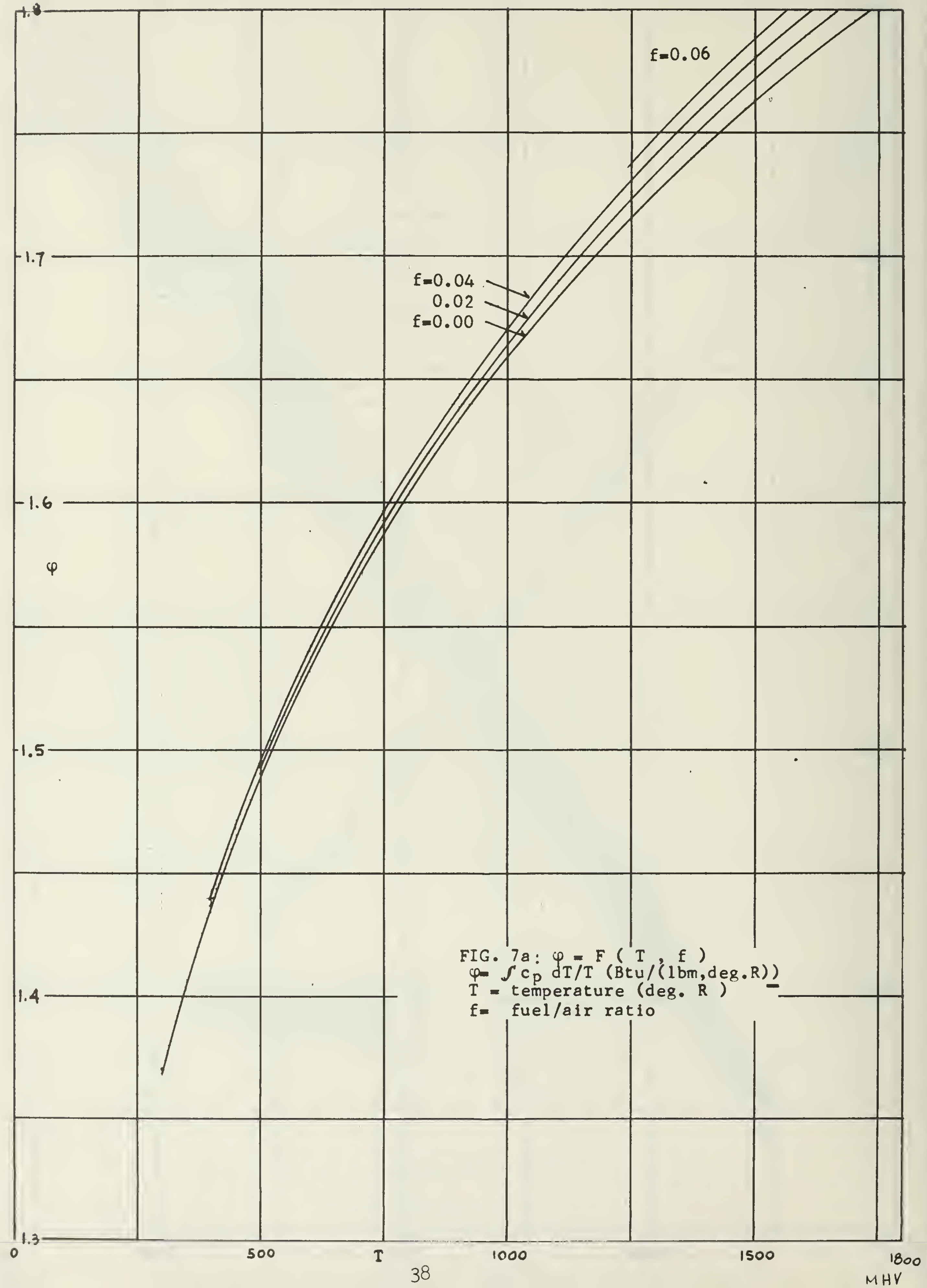


FIG. 7a: $\varphi = F(T, f)$
$\varphi = \int c_p\, dT/T$ (Btu/(lbm,deg.R))
T = temperature (deg. R)
f = fuel/air ratio

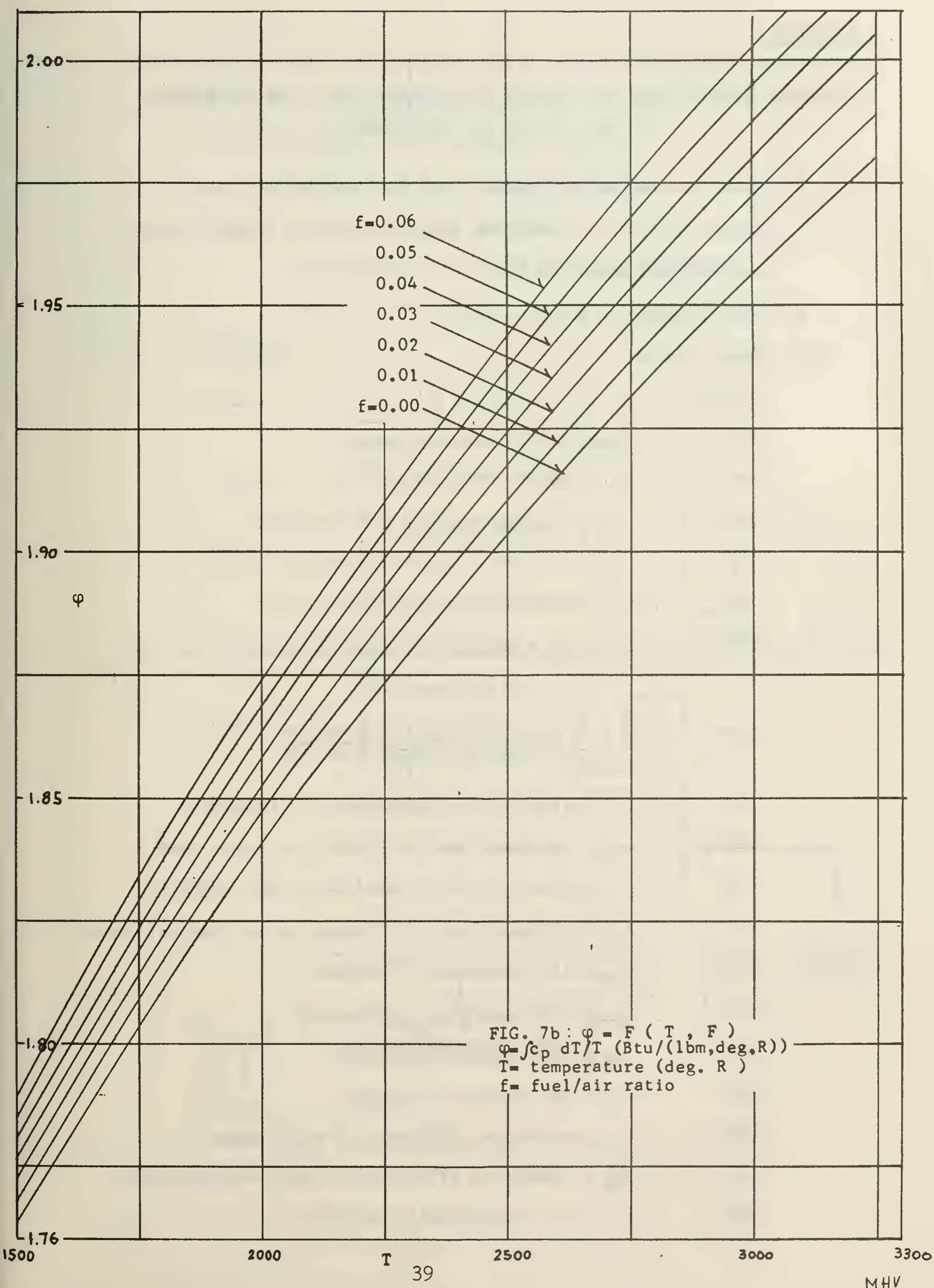


FIG. 7b : $\varphi = F(T, F)$
$\varphi = \int c_p \, dT/T$ (Btu/(lbm,deg,R))
T= temperature (deg. R)
f= fuel/air ratio

MHV

APPENDIX A

OPERATING INSTRUCTIONS OF PROGRAMS VA 513 AND VA 514 FOR JET ENGINE WITH DUCT BURNER AND AFTERBURNER

a) Enter Program VA 513 (Sides A and B of one magnetic card) at Branch Point 00. (SENSE and PRINT Switches in "down" position, and GRAD/DEG Switch at DEG)

b) Start Program at Branch Point 00.

c) Enter Data

P-COUNT	
0211	P_0 = ambient pressure (psia)
0215	T_0 = ambient temperature ($^\circ R$)
0219	P_2/P_1 = pressure ratio low compressor
0223	P_3/P_1 = overall compressor pressure ratio
0227	T_4 = turbine inlet temperature ($^\circ R$)
0231	$T_9 = T_{10}$ = temperature after afterburner and duct burner ($^\circ R$)
0235	$\xi = \frac{\dot{w}_c}{\dot{w}_E} = \frac{\text{Cooling air flow rate}}{\text{High compressor flow rate}}$
0239	λ_I = pressure loss coefficient in inlet duct
0243	λ_{BP} = pressure loss coefficient in bypass duct
0247	λ_B = pressure loss coefficient in main burner
0251	λ_{AB} = pressure loss coefficient in duct and afterburner
0255	η_{LC} = low compressor efficiency
0259	η_{HC} = high compressor efficiency
0263	η_{HT} = high turbine efficiency
0267	η_{LT} = low turbine efficiency
0271	η_B = combustion efficiency of main burner
0275	η_{AB} = combustion efficiency of duct and afterburner
0279	ψ = jet nozzle velocity coefficient

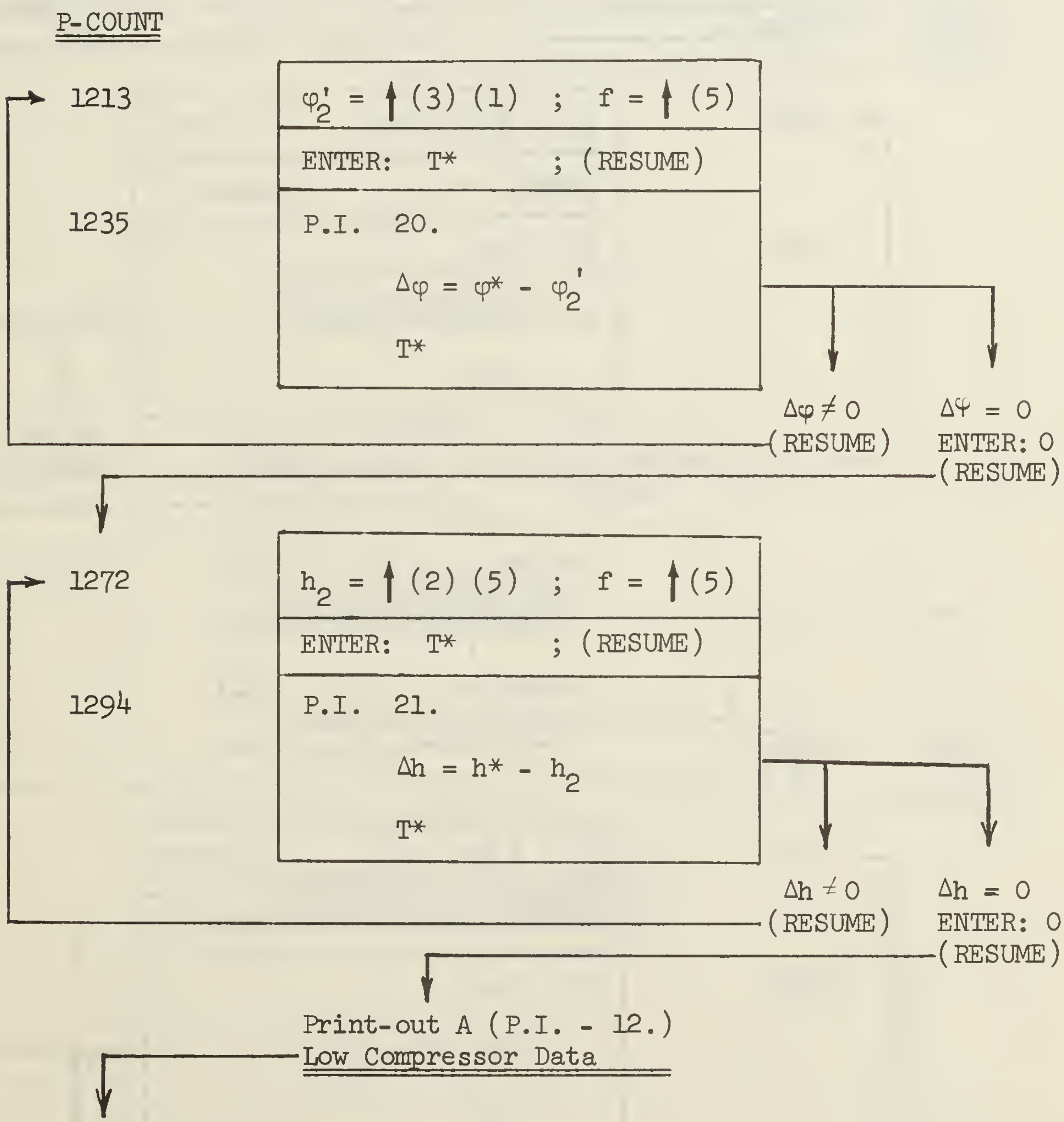
After the last entry the program prints out the above data, in the order listed, with the print identifier - 100.

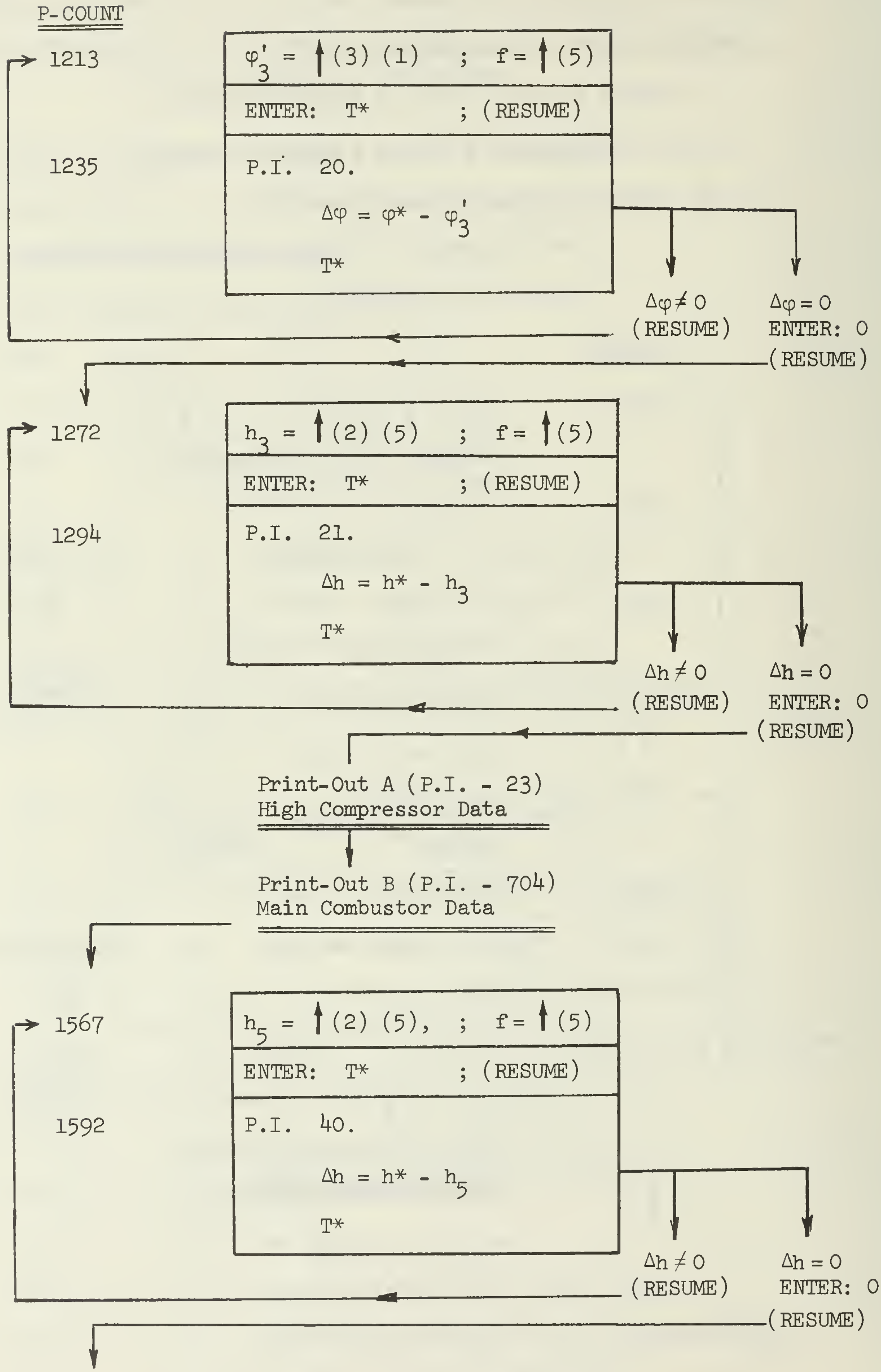
d) Enter Program VA 514 at Branch Point 00.

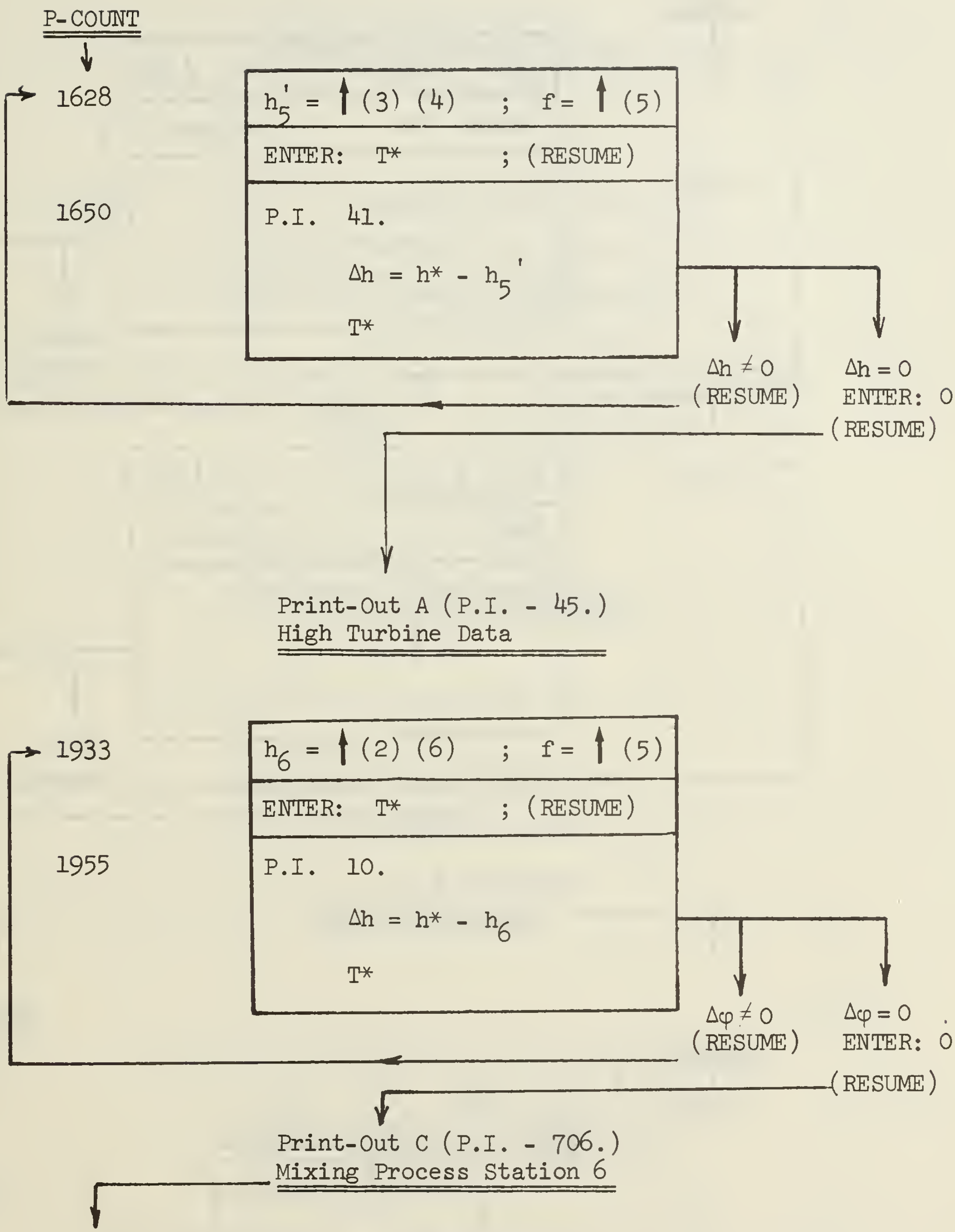
(Sides A and B of 4 magnetic cards)

e) Start Program at Branch Point 00

(For explanation of the iteration procedure see section 13 of report)




P-COUNT
1213
φ'3 = ↑(3) (1) ; f = ↑(5)
ENTER: T* ; (RESUME)
1235
P.I. 20.
Δφ = φ* - φ'3
T*
Δφ ≠ 0
(RESUME)
Δφ = 0
ENTER: 0
(RESUME)
1272
h3 = ↑(2) (5) ; f = ↑(5)
ENTER: T* ; (RESUME)
1294
P.I. 21.
Δh = h* - h3
T*
Δh ≠ 0
(RESUME)
Δh = 0
ENTER: 0
(RESUME)
Print-Out A (P.I. - 23)
High Compressor Data
Print-Out B (P.I. - 704)
Main Combustor Data
1567
h5 = ↑(2) (5), ; f = ↑(5)
ENTER: T* ; (RESUME)
1592
P.I. 40.
Δh = h* - h5
T*
Δh ≠ 0
(RESUME)
Δh = 0
ENTER: 0
(RESUME)


P-COUNT
1628
$h_5' = \uparrow (3)\ (4)$; $f = \uparrow (5)$
ENTER: T* ; (RESUME)
1650
P.I. 41.
$\Delta h = h^* - h_5'$
T*
$\Delta h \neq 0$
(RESUME)
$\Delta h = 0$
ENTER: 0
(RESUME)
Print-Out A (P.I. - 45.)
High Turbine Data
1933
$h_6 = \uparrow (2)\ (6)$; $f = \uparrow (5)$
ENTER: T* ; (RESUME)
1955
P.I. 10.
$\Delta h = h^* - h_6$
T*
$\Delta\varphi \neq 0$
(RESUME)
$\Delta\varphi = 0$
ENTER: 0
(RESUME)
Print-Out C (P.I. - 706.)
Mixing Process Station 6

P-COUNT

1361

$\varphi_8' = \uparrow(3)\ (1)$; $f = \uparrow(5)$

ENTER: T* ; (RESUME)

1383

P.I. 30.

$\Delta\varphi = \varphi^* - \varphi_8'$

T*

$\Delta\varphi \neq 0$ (RESUME)

$\Delta\varphi = 0$ ENTER: 0 (RESUME)

1419

$h_8 = \uparrow(2)\ (5)$; $f = \uparrow(5)$

ENTER: T* ; (RESUME)

P.I. 31.

$\Delta h = h^* - h_8$

T*

$\Delta h \neq 0$ (RESUME)

$\Delta h = 0$ ENTER: 0 (RESUME)

Print-Out A(P.I. -68.)
Low Turbine Data

P-COUNT

0332

P.I. -700.
Print-Out of Bypass Ratio b

If b is ok (RESUME)

If b is not ok start with new data at Step a)

Print-Out B(P.I. -710.)
Conditions after Afterburner

Station 10 of Fig. 1

0376 Check of maximum fuel/air ratio f_{10} after afterburner (last value of above print-out P.I. -710.)

If f_{10} is ok (RESUME)

If f_{10} is too large start with new data at step a.)

Print-Out B(P.I. -709.)
Conditions after Duct Burner

Print-Out C(P.I. -711.)

Conditions at Station 11
Mixed Duct Burner and
Afterburner Flows

P-COUNT

1361 $\varphi_{12}' = \uparrow(3)\ (1)$; $f = \uparrow(5)$

ENTER: T* ; (RESUME)

1383 P.I. 30.

$\Delta\varphi = \varphi^* - \varphi_{12}'$

T*

$\Delta\varphi \neq 0$ (RESUME)

$\Delta\varphi = 0$ ENTER: 0 (RESUME)

1419	$h_{12} = \uparrow(2)\ (5)$; $f = \uparrow(5)$
	ENTER: T_{12} ; (RESUME)
1441	P.J. 31. $\Delta h = h^* - h_{12}$ T^*

$\Delta h \neq 0$ (RESUME)

$\Delta h = 0$ ENTER: 0 (RESUME)

Print-Out A(P.I. -1,112.)
Exhaust Nozzle Data

Print-Out (P.I. -200.):

I_{SP} = Specific Impulse (lbf/(lbm/s))

SFC = Specific Fuel Consumption $\left(\frac{\text{lb fuel/hr}}{\text{lb thrust}}\right)$

b = Bypass Ratio

M_d = Mach Number of Flow at Exit of Jet Nozzle

P-COUNT

Data of first-stage rotor of low compressor:

0565 ENTER: D_{T1} = tip diameter (inches)

0579 " : r_{h1} = hub/tip ratio

0587 " : K_1 = blockage factor

0595 " : β_{1T} = relative flow angle at tip (°)

0608 " : U_T = peripheral speed at tip (ft/s)

To 0565

1567

$h_1 = \uparrow(2)\ (5)$; $f = \uparrow(5)$
ENTER: T^* ; (RESUME)
P.I. 40. $\Delta h = h^* - h_1$ T^*

1592

$\Delta h \neq 0$ (RESUME)

$\Delta h = 0$ ENTER: 0 (RESUME)

Print-Out A(P.I. -701.)
Inlet Duct Data

Print-Out Engine Data (P.I. -300.)

$$\left.\begin{array}{r} D_{T1} \\ r_{h1} \\ U_T \\ \beta_{1T} \\ K_1 \end{array}\right\} \quad \text{see Input above}$$

F = thrust (lbf)

$\dot{w}$ = total air flow rate (lbm/s)

HP_{LC} = horse power low compressor (HP)

HP_{HC} = horse power high compressor (HP)

M_{W1} = Mach number of relative flow at tip of first stage of low compressor

Program stops at P-Count 0565 for processing of other sets of data of first-stage rotor of low compressor.

APPENDIX B

OPERATING INSTRUCTIONS OF PROGRAMS VA 513 AND VA 514 FOR JET ENGINE WITHOUT DUCT BURNER AND WITHOUT AFTERBURNER.

In the following only the deviations from the procedure of Appendix A are indicated. In step a) ("Enter Data") of Appendix A the following changes must be made:

P-Count

.

.

.

0231 $T_9 = T_{10} = 0$

.

.

.

.

0251 λ_{AB} (can be zero or not, depending on whether the duct- and afterburner is installed, although not operating)

.

.

.

.

.

0275 $\eta_{AB} = 1.0$ (this value must be 1.0)

.

.

.

The same procedure as in Appendix A must be carried out until P-Count 0332 is reached; that is, until the bypass ratio b has been printed (P.I. -700). Then, the following steps must be carried out:

P-Count

0332 P.I. -700.

Print-Out of Bypass Ratio b

If b is ok

[↑( ) ( )]

8

0

[↓( ) ( )]

4

5

Enter on keyboard

(RESUME)

If b is not ok, start with new data at Step a) of Appendix A

Print-Out B(P.I. -710.)

Conditions at Station 10 of Fig. 1 (Identical with those at Station 8)

0376 Check of maximum fuel/air ratio

$f_{10} = f_8$ at stations 8 and 10 (last value of above print-out P.I. -710.)

If $f_8 = f_{10}$ is ok

If $f_8 = f_{10}$ is too large, start with new data at Step a) of Appendix A

$\boxed{\uparrow(\ )\ (\ )}$

8

3

$\boxed{\downarrow(\ )\ (\ )}$

2

5

Enter on keyboard

(RESUME)

Print-out B(P.I. -709.)

Conditions after Duct Burner

(Identical with those at Station 2 of Fig. 1)

1933	$h_{11} = \uparrow(2)\ (6)$; $f = \uparrow(5)$
	ENTER: T* ; (RESUME)
1955	P.J. 10. $\Delta h = h^* - h_{11}$ T*

$\Delta h \neq 0$ (RESUME)

$\Delta h = 0$ ENTER: 0 (RESUME)

Print-out C(P.I. -711)

Conditions at Station 11
Mixed Bypass and Engine Flow

(Continue with procedure of Appendix A at P-Count 1361)

(Iteration of T_{12}' for φ_{12}')

APPENDIX C. LISTING OF PROGRAMS

Program VA 513 (7 pages)

Program VA 514 (40 pages)

Contents Scratch Pad Registers (1 page)

Contents Main Data Registers (3 pages)

MONROE 1880

PROGRAM #VA513 INPUT FOR PROGR VA514 PAGE 1 OF 7 DATE: 6/73 BY: VA

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
0 0		•				
1		2				
2		4				
3		0				
4		6				
5		2	C_1			
6		↓( )( )				
7		0				
8		1			$C_1 \rightarrow 01$	
9		•				
1 0		1				
1		7				
2		7				
3		2				
4		4				
5		EXP				
6		CHSGN				
7		4	C_2			
8		↓( )( )				
9		0				
2 0		2			$C_2 \rightarrow 02$	
1		•				
2		3				
3		8				
4		0				
5		5				
6		6				
7		EXP				
8		CHSGN				
9		7	C_3			
3 0		↓( )( )				
1		0				
2		3			$C_3 \rightarrow 03$	
3		•				
4		1				
5		2				
6		6				
7		6				
8		2				
9		EXP				
4 0		CHSGN				
1		1				
2		0	C_4			
3		↓( )( )				
4		0				
5		4			$C_4 \rightarrow 04$	
6		•				
7		1				
8		3				
9		0				

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STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
5	0		1				
	1		2				
	2		EXP				
	3		CHSGN				
	4		1				
	5		4	C_5			
	6		↓( )( )				
	7		0				
	8		5	←		$C_5 \rightarrow 05$	
	9		.				
6	0		2				
	1		2				
	2		0				
	3		9				
	4		1	D_1			
	5		↓( )( )				
	6		1				
	7		1	←		$D_1 \rightarrow 11$	
	8		.				
	9		5				
7	0		1				
	1		8				
	2		2				
	3		2				
	4		EXP				
	5		CHSGN				
	6		3	D_2			
	7		↓( )( )				
	8		1				
	9		2	←		$D_2 \rightarrow 12$	
8	0		.				
	1		1				
	2		9				
	3		4				
	4		6				
	5		2				
	6		EXP				
	7		CHSGN				
	8		6	D_3			
	9		↓( )( )				
9	0		1				
	1		3	←		$D_3 \rightarrow 13$	
	2		.				
	3		4				
	4		5				
	5		0				
	6		8				
	7		9				
	8		EXP				
	9		CHSGN				

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STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
10	0		1				
	1		0	D_4			
	2		↓( )( )				
	3		1				
	4		4	←		$D_4 \rightarrow 14$	
	5		•				
	6		4				
	7		3				
	8		2				
	9		7				
11	0		5				
	1		EXP				
	2		CHSGN				
	3		1				
	4		4				
	5		↓( )( )				
	6		1				
	7		5	←		$D_5 \rightarrow 15$	
	8		5				
	9		•				
12	0		0				
	1		3				
	2		5				
	3		2				
	4		3				
	5		3				
	6		EXP				
	7		CHSGN				
	8		1	$J/R = 778.16/1545.43$			
	9		↓( )( )				
13	0		0				
	1		0	←		$J/R \rightarrow 00$	
	2		3				
	3		•				
	4		4				
	5		5				
	6		2				
	7		2				
	8		EXP				
	9		CHSGN				
14	0		2	$a = .034522$			
	1		↓( )( )				
	2		0				
	3		6			$a \rightarrow 06$	
	4		3				
	5		•				
	6		5				
	7		6				
	8		4				
	9		8				

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STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
150		EXP				
1		CHSGN				
2		2	b = .035648			
3		↓( )( )				
4		0				
5		7	←		b → 07	
6		1				
7		.				
8		8				
9		4				
160		EXP				
1		4	LHV = 18400			
2		↓( )( )				
3		0				
4		8	←		LHV → 08	
5		2				
6		6				
7		0	h_f = 260			
8		↓( )( )				
9		0				
170		9	←		h_f → 09	
1		7				
2		7				
3		8				
4		.				
5		1				
6		6	J			
7		↓( )( )				
8		1				
9		0	←		J → 10	
180		×				
1		2				
2		×	2 J			
3		3				
4		2				
5		.				
6		1				
7		7				
8		4	g		g	
9		↓( )( )				
190		1				
1		6			g → 16	
2		=	2g J			
3		↓( )( )				
4		1				
5		8			2gJ → 18	
6		↑( )( )				
7		1				
8		0	J			
9		÷				

MHY 2/7/73

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
200		5				
1		5				
2		0				
3		=	J/550			
4		↓( )( )				
5		1				
6		7			J/550 → 17	
7		SET D.P				
8		4				
9	EC	377	NO OP			
210		HALT	P_0 (psia)	P_0		
1		↓( )( )				
2		4				
3		0			$P_0 \rightarrow 40$	
4		HALT	T_0 (°R)	T_0		
5		↓( )( )				
6		4				
7		1			$T_0 \rightarrow 41$	
8		HALT	P_2/P_1	P_2/P_1		
9		↓( )( )				
220		4				
1		2			$P_2/P_1 \rightarrow 42$	
2		HALT	P_3/P_1	P_3/P_1		
3		↓( )( )				
4		4				
5		3			$P_3/P_1 \rightarrow 43$	
6		HALT	T_4 (°R)	T_4		
7		↓( )( )				
8		4				
9		4			$T_4 \rightarrow 44$	
230		HALT	$T_9 = T_{10}$ (°R)	$T_9 = T_{10}$		
1		↓( )( )				
2		4				
3		5			$T_9 = T_{10} \rightarrow 45$	
4		HALT	ξ	ξ		
5		↓( )( )				
6		4				
7		6			$\xi \rightarrow 46$	
8		HALT	λ_I	λ_I		
9		↓( )( )				
240		4				
1		7			$\lambda_I \rightarrow 47$	
2		HALT	λ_{BP}	λ_{BP}		
3		↓( )( )				
4		4				
5		8			$\lambda_{BP} \rightarrow 48$	
6		HALT	λ_B	λ_B		
7		↓( )( )				
8		4				
9		9			$\lambda_B \rightarrow 49$	

STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
25	0		HALT	$\lambda_{DB} = \lambda_{AB}$	$\lambda_{DB}=\lambda_{AB}$		
	1		↓( )( )				
	2		5				
	3		0			$\lambda_{AB} \rightarrow 50$	
	4		HALT	η_{LC}	η_{LC}		
	5		↓( )( )				
	6		5				
	7		1			$\eta_{LC} \rightarrow 51$	
	8		HALT	η_{HC}	η_{HC}		
	9		↓( )( )				
26	0		5				
	1		2			$\eta_{HC} \rightarrow 52$	
	2		HALT	η_{HT}	η_{HT}		
	3		↓( )( )				
	4		5				
	5		3			$\eta_{HT} \rightarrow 53$	
	6		HALT	η_{LT}	η_{LT}		
	7		↓( )( )				
	8		5				
	9		4			$\eta_{LT} \rightarrow 54$	
27	0		HALT	η_{B}	η_{B}		
	1		↓( )( )				
	2		5				
	3		5			$\eta_{B} \rightarrow 55$	
	4		HALT	η_{AB}	η_{AB}		
	5		↓( )( )				
	6		5				
	7		6			$\eta_{AB} \rightarrow 56$	
	8		HALT	ψ_N	ψ_N		
	9		↓( )( )				
28	0		5				
	1		7			$\psi_N \rightarrow 57$	
	2	EC	176	1 LINE OF DOTS			
	3		ADVANCE				
	4		4				
	5		1	POINTER 41			
	6		↓( )( )				
	7		5				
	8		9	STORE PT. 41 in 59			
	9		↓( )				
29	0		•	SET UP PT 41			
	1		↑( )( )				
	2		4				
	3		0	P_0			
	4		1				
	5		0	PRINT IDENTIFIER −100.			
	6		0				
	7		•				
	8		CHSGN				
	9	EC	177				100.

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STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
300		PRINT A				P_0
1	√	IND/SYMB	SYMBOL. ADDRESS √			
2		√				
3		↑( )( )	RCL & PRINT ACCORDING TO			
4		IND/SYMB	POINTER			
5		PRINT A				
6		1	1			
7		↑( )( )	ADD 1 TO POINTER STR(E)			
8		+				
9		5				
310		9				
1		↓( )( )				
2		5				
3		9	STR NEW POINTER IN REG. 59		PT → 59	
4		↓( )				
5		•	SET UP NEW POINTER			
6		−				
7		5				
8		8				
9		=	NEW POINTER − 59			
320		JUMP				
1		=				
2		IND/SYMB				
3		÷				
4		JUMP				
5		IND/SYMB				
6		√				
7	÷	IND/SYMB				
8		÷				
9		SET D.P.				
330		6	SET D.P. TO 6 FOR VA 514			
1	EC	176	1 LINE OF DOTS			• • • •
2		HALT	CHECK OF INPUT DATA			
3						
4						
5						
6						
7						
8						
9						
340						
1						
2						
3						
4						
5						
6						
7						
8						
9						

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STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
000		↑( )( )				
1		4				
2		1	T_o			
3		↓( )( )				
4		2				
5		1			$T_o \rightarrow 21$	
6		↑( )( )				
7		4				
8		2	P_2/P_1			
9		↓( )( )				
010		2				
1		0			$P_2/P_1 \rightarrow 20$	
2		↑( )( )				
3		5				
4		1	η_{LC}			
5		↓( )( )				
6		2				
7		3	–		$\eta_{LC} \rightarrow 23$	
8		1				
9		2				
020		.				
1		CHSGN	PRINT IDENTIF. -12 FOR LC			
2		↓( )( )	STR (36			
3		3				
4		6			PI → 36	
5	EC	016	SET FLAG 1			
6	EC	377	NO OP.			
7		JUMP	GO TO SUBROUTINE ÷ COMPRESSOR (LC)			
8		IND/SYM				-12
9		÷				LC DATA
030	EC 040	IND/SYM	SYMB. ADDRESS EC 040			
1	EC	040				
2	EC	166	RESET FLAG 1			
3		↑( )( )				
4		2				
5		6	$h_2 - h_1$			
6		↓( )( )				
7		7				
8		0			$h_2 - h_1 \rightarrow 70$	
9		↑( )( )				
040		2				
1		4	T_2			
2		↓( )( )				
3		8				
4		3			$T_2 \rightarrow 83$	
5		↓( )( )				
6		2				
7		1			$T_2 \rightarrow 21$	
8		↑( )( )				
9		4				

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STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
050	0		3	P_3/P_1			
	1		÷				
	2		↑( )( )				
	3		4				
	4		2	P_2/P_1			
	5		=	P_3/P_2			
	6		↓( )( )				
	7		2				
	8		0			$P_3/P_2 \rightarrow 20$	
	9		↑( )( )				
060	0		5				
	1		2	η_{HC}			
	2		↓( )( )				
	3		2				
	4		3			$\eta_{HC} \rightarrow 23$	
	5		2				
	6		3	PRINT IDENTIF. -23. FOR HC			
	7		.	STR (36)			
	8		CHSGN				
	9		↓( )( )				
070	0		3				
	1		6			PI → 36	
	2		JUMP	GO TO SUBROUTINE ÷ "COMPRESSOR" (HC)			
	3		IND/SYM				-23
	4		÷				HC DATA
	5	EC 041	IND/SYMB				
	6	EC	041				
	7		↑( )( )				
	8		2				
	9		6	h_3-h_2			
080	0		↓( )( )				
	1		7				
	2		1			$h_3-h_2 \rightarrow 71$	
	3		↑( )( )				
	4		2				
	5		4	T_3			
	6		↓( )( )				
	7		7				
	8		2			$T_3 \rightarrow 72$	
	9		↓( )( )				
090	0		2				
	1		0		T_3	$= T_i \rightarrow 20$	
	2		0	0			
	3		↓( )( )				
	4		2		f_i	$= 0 \rightarrow 21$	
	5		1	$f_i = 0$			
	6		↑( )( )				
	7		4				
	8		4	$T_4 = T_e$			
	9		↓( )( )				

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STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
100		2				
1		5			$T_4 = T_c \rightarrow 25$	
2		↑( )( )				
3		5				
4		5	η_B			
5		↓( )( )				
6		2			$\eta_B \rightarrow 22$	
7		2				
8		7				
9		0				
110		4	PRINT IDENTIF. −704 FOR			
1		CHSGN	MAIN BURNER EXIT			
2		↓( )( )				
3		2				
4		9			$PI \rightarrow 29$	
5		BRANCH	CALL SUBROUTINE "BURNER"			
6		IND/SYMB	FOR MAIN COMBUSTOR			-704
7		a^x				PRINT
8		↑( )( )				
9		2				
120		7	$\Delta f = f_B'$			
1		↓( )( )				
2		7				
3		3			$f_B' \rightarrow 73$	
4		↓( )( )				
5		2				
6		7			$f_B' \rightarrow 27$	
7		+				
8		1				
9		x	$1 + f_B'$			
130		(				
1		1				
2		−				
3		↑( )( )				
4		4				
5		6	ξ			
6		)	$1 - \xi$			
7		=	$(1 + f_B')(1 - \xi)$			
8		INV				
9		x				
140		↑( )( )				
1		7				
2		1	$h_3 - h_2$			
3		=	$\Delta h = h_4 - h_5$			
4		↓( )( )				
5		2				
6		6			$h_4 - h_5 \rightarrow 26$	
7		↑( )( )				
8		5				
9		3	η_{HT}			

STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
15	0		↓( )( )				
	1		2				
	2		3			$\eta_{HT} \to 23$	
	3		4				
	4		5	PRINT IDENTIF. −45 FOR HT			
	5		CHSGN	STR(36)			
	6		↓( )( )				
	7		3				
	8		6			PI → 36	
	9		↑( )( )				
16	0		4				
	1		4	T_4			
	2		↓( )( )				
	3		2				
	4		1			$T_4 \to 21$	
	5	EC	016	SET FLAG 1			
	6		JUMP				
	7		IND/SYMB	GO TO SUBROUTINE HT			−45
	8		π/e				DATA
	9	EC042	IND/SYMB	SYMB. ADDRESS EC 042			
17	0	EC	042				
	1	EC	166	RESET FLAG 1			
	2		↑( )( )				
	3		2				
	4		0	P_5/P_4			
	5		↓( )( )				
	6		7				
	7		4			$P_5/P_4 \to 74$	
	8		↑( )( )				
	9		2				
18	0		4	T_5			
	1		↓( )( )				
	2		7				
	3		5			$T_5 \to 75$	
	4		↓( )( )				
	5		2				
	6		0			$T_5 = T_i \to 20$	
	7		↑( )( )				
	8		7				
	9		3	f_B'			
19	0		↓( )( )				
	1		2				
	2		1		f_i=	$f_B' \to 21$	
	3		↑( )( )				
	4		7				
	5		2	T_3			
	6		↓( )( )				
	7		2				
	8		2		T_3	$= T_{ii} \to 22$	
	9		0	0			

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STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
200		↓( )( )				
1		2				
2		3			$f_{ii} = 0 \to 23$	
3		↑( )( )				
4		4				
5		6	ξ			
6		÷				
7		(				
8		1				
9		−				
210		↑( )( )				
1		4				
2		6	ξ			
3		)	$1 - \xi$			
4		=	$\zeta = \xi/(1-\xi)$			
5		↓( )( )				
6		2				
7		7			$\zeta \to 27$	
8		7				
9		0				
220		6	PRINT IDENTIF. -706			
1		CHSGN	FOR STATION 6			
2		↓( )( )	STR (29)			
3		2				
4		9			PI → 29	
5	EC	016	SET FLAG 1			
6		JUMP	GO TO SUBROUTINE "MIXING" FOR			
7		IND/SYMB	STATION 6 AFTER HT			
8		Φ				
9	EC 043	IND/SYMB	SYMBOL. ADDRESS EC 043			
230	EC	043				
1	EC	166	RESET FLAG 1			
2		↑( )( )				
3		2				
4		5	T_6			
5		↓( )( )				
6		2				
7		1			$T_6 = T_i \to 21$	
8		↑( )( )				
9		2				
240		8	$f_B = f_e$			
1		↓( )( )				
2		2			$f_B = f_e \to 27$	
3		7				
4		↑( )( )				
5		5				
6		4	η_{LT}			
7		↓( )( )				
8		2				
9		3		$\eta_e =$	$\eta_{LT} \to 23$	

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
250		1	1			
1		−				
2		↑( )( )				
3		4				
4		8	λ_{BP}			
5		÷	$1-\lambda_{BP}$			
6		(				
7		1	1			
8		−				
9		↑( )( )				
260		4				
1		9	λ_B			
2		)	$1-\lambda_B$			
3		x				
4		↑( )( )				
5		4				
6		2	P_2/P_1			
7		÷				
8		↑( )( )				
9		4				
270		3	P_3/P_1			
1		÷				
2		↑( )( )				
3		7				
4		4	P_5/P_4			
5		=	P_8/P_5			
6		↓( )( )				
7		7				
8		6			$P_8/P_5 \rightarrow 76$	
9		↓( )( )				
280		2				
1		0			$P_8/P_5 \rightarrow 20$	
2		6				
3		8	PRINT IDENTIF. −68 FOR LT			
4		CHSGN				
5		↓( )( )				
6		3				
7		6			PI → 36	
8	EC	016	SET FLAG 1			
9		JUMP	GO TO SUBROUTINE "EXPANS."			
290		IND/SYMB	FOR LT			−68
1		X				PRINT
2	EC 044	IND/SYMB	SYMBOL. ADDRESS EC 044			
3	EC	044				
4	EC	166	RESET FLAG 1			
5		↑( )( )				
6		2				
7		6	h_6-h_8			
8		↓( )( )				
9		7				

STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
30	0		8				
	1		×				
	2		(				
	3		1	1			
	4		+				
	5		↑( )( )				
	6		2				
	7		7	f_B			
	8		↓( )( )				
	9		7				
31	0		7			$f_B \rightarrow 77$	
	1		↓( )( )				
	2		2				
	3		1			$f_B \rightarrow 21$	
	4		)	$1+f_B$			
	5		÷				
	6		↑( )( )				
	7		7				
	8		0	h_2-h_1			
	9		−				
32	0		1				
	1		=	b			
	2		↓( )( )				
	3		7				
	4		9			$b \rightarrow 79$	
	5		7				
	6		0				
	7		0	P.I. -700.			
	8		CHSGN				
	9	EC	177				-700.
33	0		PRINTA				b
	1		HALT	Check b: Without AB: ↑(8)(0) ↓(4)(5)			
	2		↑( )( )				
	3		2				
	4		4	T_B			
	5		↓( )( )				
	6		8				
	7		0			$T_B \rightarrow 80$	
	8		↓( )( )				
	9		2				
34	0		0		T_B	$= T_i \rightarrow 20$	
	1		↑( )( )				
	2		5				
	3		6	η_{AB}			
	4		↓( )( )				
	5		2				
	6		2		η_A	$_B \rightarrow 22$	
	7		↑( )( )				
	8		4				
	9		5	T_9			

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STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
35	0		↓( )( )				
	1		2				
	2		5		T_e =	T_9 → 25	
	3		7				
	4		1	P.I. -710.			
	5		0	CONDITIONS STATION 10			
	6		CHSGN	AFTER A.B.			
	7		↓( )( )				
	8		2				
	9		9			P.I → 29	
36	0		BRANCH	CALL S.R. "BURNER", a^x			
	1		IND/SYMB	FOR AB.			-710
	2		a^x				DATA
	3		↑( )( )				
	4		2				
	5		7	Δf_{AB}			
	6		↓( )( )				
	7		8				
	8		1			Δf_{AB} → 81	
	9		↑( )( )				
37	0		2				
	1		8	f_e			
	2		↓( )( )				
	3		8				
	4		2			f_e → 82	
	5		HALT	CHECK f_{max}? Without AB: ↑(8)(3)↓(2)(5)			
	6		↑( )( )				
	7		8				
	8		3	$T_2 = T_i$			
	9		↓( )( )				
38	0		2				
	1		0		T_2	= T_i → 20	
	2		0	$f_i = 0$			
	3		↓( )( )				
	4		2				
	5		1		0 =	f_i → 21	
	6		7				
	7		0	P.I. -709			
	8		9	CONDITIONS STATION 9			
	9		CHSGN	AFTER DUCT BURNER			
39	0		↓( )( )				
	1		2				
	2		9			P.I → 29	
	3		BRANCH	CALL S.R. "BURNER", a^x			
	4		IND/SYMB	FOR D.B.			-709
	5		a^x				DATA
	6		↑( )( )				
	7		2				
	8		8	f_{DB}			
	9		↓( )( )				

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STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
400		2		f_{DB}	$= f_{ii} \rightarrow 23$	
1		3				
2		↑( )( )				
3		8				
4		2	$f_B + f_{AB}$			
5		↓( )( )				
6		2		$f_B +$	$f_{AB} = f_i \rightarrow 21$	
7		1				
8		↑( )( )				
9		4				
410		5	$T_9 = T_{10}$			
1		↓( )( )				
2		2		$T_9 =$	$T_i \rightarrow 20$	
3		0	$T_i = T_9$			
4		↑( )( )				
5		2				
6		5	T_e from S.R. D.B = T_{ii}			
7		↓( )( )				
8		2				
9		2			$T_{ii} \rightarrow 22$	
420		7				
1		1	P.I. -711			
2		1	CONDITIONS STATION 11			
3		CHSGN	MIXED AB & DB FLOWS			
4		↓( )( )				
5		2				
6		9			P.I → 29	
7		↑( )( )				
8		7				
9		9	$b = \xi$			
430		↓( )( )				
1		2				
2		7			$b = \xi \rightarrow 27$	
3		JUMP	TO S.R. "MIXING", Φ			
4		IND/SYMB	MIXING OF AB & DB FLOWS			-711
5		Φ				DATA
6	EC 045	IND/SYMB	SYMB. ADDRESS EC 045			
7	EC	045				
8		↑( )( )				
9		2				
440		8	$f_e = f_N$			
1		↓( )( )				
2		8				
3		4			$f_N \rightarrow 84$	
4		↓( )( )				
5		2				
6		7		$f =$	$f_N \rightarrow 27$	
7		↑( )( )				
8		5				
9		7	ψ_N			

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STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
45	0		x				
	1		=	$\Psi_N^2 = \eta_N$			
	2		↓( )( )				
	3		2				
	4		3			$\eta_N \rightarrow 23$	
	5		↑( )( )				
	6		2				
	7		5	$T_9 = T_i$			
	8		↓( )( )				
	9		2		T_9	$=T_i \rightarrow 21$	
46	0		1				
	1		1	1			
	2		−				
	3		↑( )( )				
	4		4				
	5		7	λ_J			
	6		x				
	7		(				
	8		1	1			
	9		−				
47	0		↑( )( )				
	1		4				
	2		8	λ_{BP}			
	3		)	$1-\lambda_{BP}$			
	4		x				
	5		(				
	6		1	1			
	7		−				
	8		↑( )( )				
	9		5				
48	0		0	λ_{AB}			
	1		)	$1-\lambda_{AB}$			
	2		x				
	3		↑( )( )				
	4		4				
	5		2	P_2/P_1			
	6		=	P_{11}/P_{12}			
	7		1/x	P_{12}/P_{11}			
	8		↓( )( )				
	9		2				
49	0		0			$P_{12}/P_{11} \rightarrow 20$	
	1		1				
	2		1	P.I. −1112			
	3		1	FOR EXHAUST NOZZLE			
	4		2				
	5		CHSGN				
	6		↓( )( )				
	7		3				
	8		6			I.P. → 36	
	9		JUMP				

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STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
50	0		IND/SYMB	TO S.R. "EXPANSION", X			-1112
	1		x	FOR JET NOZZLE			DATA
	2	EC 046	IND/SYMB	SYMB. ADDRESS EC 046			
	3	EC	046				
	4		↑( )( )				
	5		3				
	6		4	V_d			
	7		x				
	8		(				
	9		1	1			
51	0		+				
	1		↑( )( )				
	2		8				
	3		4	f_N			
	4		)	$1+f_N$			
	5		÷				
	6		↑( )( )				
	7		1				
	8		6	g			
	9		=	I_{sp}			
52	0		↓( )( )				
	1		8				
	2		5			$I_{SP} \to 85$	
	3		↓( )( )				
	4		2				
	5		5			$I_{SP} \to 25$	
	6		1/x	$1/I_{SP}$			
	7		x				
	8		↑( )( )				
	9		8				
53	0		4	f_N			
	1		x				
	2		3				
	3		6				
	4		0				
	5		0	3600			
	6		=	SFC			
	7		↓( )( )				
	8		2				
	9		6			SFC → 26	
54	0		↑( )( )				
	1		7				
	2		9	b			
	3		↓( )( )				
	4		2				
	5		7			b → 27	
	6		↑( )( )				
	7		3				
	8		5	M_d			
	9		↓( )( )				

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STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
55	0		2				
	1		8			$M_d \to 28$	
	2		2				
	3		0	P.I. -200			
	4		0	FOR OVERALL PERFORMANCE			
	5		CHSGN				
	6		↓( )( )				
	7		2				
	8		9			P.I. → 29	
	9		BRANCH				
56	0		IND/SYMB	CALL S.R. "PRINT II", ↑( )			-200
	1		↑( )	FOR OVERALL PERFORMANCE			DATA
	2	EC 060	IND/SYMB	SYMB. ADDRESS EC 060			
	3	EC	060				
	4		HALT	D_{T1}	D_{T1}		
	5		↓( )( )				
	6		6				
	7		0			$D_{T1} \to 60$	
	8		x				
	9		x				
57	0		π				
	1		÷				
	2		4				
	3		x				
	4		(				
	5		1	1			
	6		–				
	7		(				
	8		HALT	r_{h1}	r_{h1}		
	9		↓( )( )				
58	0		6				
	1		1			$r_{h1} \to 61$	
	2		x				
	3		)	r_{h1}^2			
	4		)	$1 - r_{h1}^2$			
	5		x				
	6		HALT	k_1	k_1		
	7		↓( )( )				
	8		6				
	9		4			$k_1 \to 64$	
59	0		=	$C = \frac{\pi}{4} D_{T1}^2 (1 - r_{h1}^2)$			
	1		↓( )( )				
	2		9				
	3		2			$C \to 92$	
	4		HALT	β_{1T}	β_{1T}		
	5		↓( )( )				
	6		6				
	7		3			$\beta_{1T} \to 63$	
	8		SIN/COS	$\sin \beta_{1T}$			
	9		↓( )( )				

STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
600	0		9				
	1		0		sin	$\beta_{1T} \rightarrow 90$	
	2		÷				
	3		2ND FUNC	$\cos\beta_{1T}$			
	4		=	$\tan\beta_{1T}$			
	5		1/x	$\cot\beta_{1T}$			
	6		X				
	7		HALT	U_T	U_T		
	8		↓( )( )				
	9		6				
610	0		2				
	1		X	$U_T \cot\beta_{1T}$		$U_T \rightarrow 62$	
	2		↓( )( )				
	3		9				
	4		1		U_T	$\cot\beta_{1T} \rightarrow 91$	
	5		÷	$(U_T \cot\beta_{1T})^2$			
	6		↑( )( )				
	7		1				
	8		8	$2gJ$			
	9		=	$h_1 - h_{s1} = \Delta h$			
620	0		↓( )( )				
	1		2				
	2		6			$\Delta h \rightarrow 26$	
	3		↑( )( )				
	4		4				
	5		1	$T_0 = T_1$			
	6		↓( )( )				
	7		2				
	8		1			$T_1 = T_i \rightarrow 21$	
	9		1	$\eta = 1$			
630	0		↓( )( )				
	1		2				
	2		3			$\eta = 1 \rightarrow 23$	
	3		0	$0 = f$			
	4		↓( )( )				
	5		2		0	$= f \rightarrow 27$	
	6		7				
	7		1	P.I. -101			
	8		0	INLET DUCT			
	9		1				
640	0		CHSGN				
	1		↓( )( )				
	2		3				
	3		6				
	4		JUMP	TO S.R. "EXPANSION", π/e			
	5		IND/SYMB	FOR INLET DUCT			-101
	6		π/e				DATA
	7	EC 047	IND/SYMB	SYMB. ADDRESS EC 047			
	8	EC	047				
	9		↑( )( )				

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STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
650		2				
1		0	$P_{S1}/P_1 = P_e/P_i$			
2		x				
3		(				
4		1	1			
5		−				
6		↑( )( )				
7		4				
8		7	λ_I			
9		)	$1-\lambda_I$			
660		x				
1		↑( )( )				
2		4				
3		0	P_0			
4		÷				
5		↑( )( )				
6		2				
7		9	R_G			
8		÷				
9		↑( )( )				
670		2				
1		4	T_{S1}			
2		x				
3		↑( )( )				
4		9				
5		1	$U_T \cot \beta_{1T}$			
6		x				
7		↑( )( )				
8		9				
9		2	C			
680		x	$\dot{w}$			
1		↓( )( )				
2		6				
3		6			$\dot{w} \rightarrow 66$	
4		↑( )( )				
5		8				
6		5	I_{SP}			
7		=	F			
8		Φ	delete fractions of F			
9		5				
690		↓( )( )				
1		6				
2		5			$F \rightarrow 65$	
3		↑( )( )				
4		6				
5		2	U_T			
6		÷				
7		↑( )( )				
8		9				
9		0	$\sin\beta_{1T}$			

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
700		÷	$W_1 = U_T / \sin\beta_{1T}$			
1		↑( )( )				
2		3				
3		5	a_{s1}			
4		=	M_{W1}			
5		↓( )( )				
6		6				
7		9			$M_{W1} \rightarrow 69$	
8		↑( )( )				
9		6				
710		6	$\dot{w}$			
1		x				
2		↑( )( )				
3		1				
4		7	J/550			
5		x	$\dot{w}$ J/550			
6		↑( )( )				
7		7				
8		0	$h_2 - h_1$			
9		=	HP_{LC}			
720		Φ	delete fractions of HP_{LC}			
1		5				
2		↓( )( )				
3		6				
4		7			$HP_{LC} \rightarrow 67$	
5		↑( )( )				
6		7				
7		1	$h_3 - h_2$			
8		=	$(\dot{w}\ J/550)(h_3 - h_2)$			
9		÷				
730		(				
1		1	1			
2		+				
3		↑( )( )				
4		7				
5		9	b			
6		)	1 + b			
7		=	HP_{HC}			
8		Φ	delete fractions of HP_{HC}			
9		5				
740		↓( )( )				
1		6				
2		8			$HP_{HC} \rightarrow 68$	
3		6	POINTER 61 STR (59)			
4		1				
5		↓( )( )				
6		5				
7		9			PT → 59	
8		↓( )	SET UP POINTER 61			
9		•				

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
750		↑( )( )				
1		6				
2		0	D_{T1}			
3		3				
4		0				
5		0	P.I. - 300			
6		CHSGN				
7	EC	177				-300
8		PRINT A				D_{T1}
9	EC 062	IND/SYMB	SYMB. ADDRESS EC 062			
760	EC	062				
1		↑( )( )	RCL ACCORD. TO POINTER			
2		IND/SYMB				
3		PRINT A				PRINT
4		1	1			POINTER
5		↑( )( )				
6		+				
7		5				
8		9	ADD 1 TO POINTER, STR (E)			
9		↓( )( )				
770		5				
1		9	STR POINTER IN 59		POINT. → 59	
2		↓( )				
3		•	SET UP NEW POINTER			
4		−				
5		7				
6		0	70			
7		=	NEW POINTER −70			
8		BRANCH				
9		=	GO TO S.A. EC 063 IF NEW POINTER			
780		IND/SYMB	EQUALS 70			
1	EC	063				
2		JUMP	GO TO S.A. EC 062 IF NEW POINTER			
3		IND/SYMB	$\leq$ 69			
4	EC	062				
5	EC 063	IND/SYMB	SYMB. ADDRESS EC 063			
6	EC	063				
7	EC	176		END		....
8	EC	176	3 LINES OF DOTS	MAIN		....
9	EC	176		PROGR		....
790		ADVANCE	2 PAPER ADVANCE			
1		ADVANCE				
2		JUMP	TO INTRODUCE OTHER FIRST-STAGE			
3		IND/SYMB	LC ROTOR DATA			
4	EC	060				
5	−	IND/SYMB	SUBROUTINE φ, (−)		T in 0	
6		−			t in 5	
7		↑( )				
8		0	T			
9		ln/log	ln T			

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STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
80	0		×				
	1		↑( )( )				
	2		0				
	3		1	C_1			
	4		−	$C_1 \ln T$			
	5		(				
	6		↑( )				
	7		0	T			
	8		×				
	9		↑( )( )				
81	0		0				
	1		2	C_2			
	2		)	$C_2 T$			
	3		+				
	4		(				
	5		↑( )				
	6		0	T			
	7		×				
	8		÷	T^2			
	9		2				
82	0		×	$T^2/2$			
	1		↓( )				
	2		1			$T^2/2 \rightarrow 1$	
	3		↑( )( )				
	4		0				
	5		3	C_3			
	6		)	$C_3 T^2/2$			
	7		−				
	8		(				
	9		↑( )				
83	0		0	T			
	1		a^x				
	2		3				
	3		÷	T^3			
	4		3				
	5		×	$T^3/3$			
	6		↓( )				
	7		2			$T^3/3 \rightarrow 2$	
	8		↑( )( )				
	9		0				
84	0		4	C_4			
	1		)	$C_4 T^3/3$			
	2		+				
	3		(				
	4		↑( )				
	5		0	T			
	6		a^x				
	7		4				
	8		÷	T^4			
	9		4				

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
850		x	$T^4/4$			
1		↓( )				
2		3			$T^4/4 \to 3$	
3		↑( )( )				
4		0				
5		5	C_5			
6		)	$C_5\ T^4/4$			
7		=	φ_A			
8		↓( )				
9		6			$\varphi_A \to 6$	
860		↑( )				
1		0	T			
2		ln/log	ln T			
3		x				
4		↑( )( )				
5		1				
6		1	D_1			
7		+	D_1 ln T			
8		(				
9		↑( )				
870		0	T			
1		x				
2		↑( )( )				
3		1				
4		2	D_2			
5		)	$D_2\ T$			
6		−				
7		(				
8		↑( )				
9		1	$T^2/2$			
880		x				
1		↑( )( )				
2		1				
3		3	D_3			
4		)	$D_3\ T^2/2$			
5		+				
6		(				
7		↑( )				
8		2	$T^3/3$			
9		x				
890		↑( )( )				
1		1				
2		4	D_4			
3		)	$D_4\ T^3/3$			
4		−				
5		(				
6		↑( )				
7		3	$T^4/4$			
8		x				
9		↑( )( )				

STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
90	0		1				
	1		5	D_S			
	2		)	$D_S\ T^4/4$			
	3		x	φ_G			
	4		↑( )				
	5		5	f			
	6		+	$f\ \varphi_G$			
	7		↑( )				
	8		6	φ_A			
	9		÷				
91	0		(				
	1		1	1			
	2		+				
	3		↑( )				
	4		5	f			
	5		)	$1+f$			
	6		=	$\varphi = [\varphi_A + f\varphi_G]/(1+f)$			
	7		↓( )	END S.R.			
	8		7	φ		$\varphi \to 7$	
	9		RESUME				
92	0	+	IND/SYMB	SUBROUTINE h_A, h_G, h (+)		T in 0 f in 5	
	1		+				
	2		↑( )				
	3		0	T			
	4		x				
	5		↑( )( )				
	6		0				
	7		1	C_1			
	8		−	$C_1\ T$			
	9		(				
93	0		↑( )				
	1		0	T			
	2		x				
	3		÷	T^2			
	4		2				
	5		X	$T^2/2$			
	6		↓( )				
	7		1			$T^2/2 \to 1$	
	8		↑( )( )				
	9		0				
94	0		2	C_2			
	1		)	$C_2\ T^2/2$			
	2		+				
	3		(				
	4		↑( )				
	5		0	T			
	6		a^x				
	7		3				
	8		÷	T3			
	9		3				

STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
95	0		x	$T^3/3$			
	1		↓( )				
	2		2			$T^3/3 \rightarrow 2$	
	3		↑( )( )				
	4		0				
	5		3	C_3			
	6		)	$C_3\, T^3/3$			
	7		−				
	8		(				
	9		↑( )				
96	0		0	T			
	1		a^x				
	2		4				
	3		÷	T^4			
	4		4				
	5		x	$T^4/4$			
	6		↓( )				
	7		3			$T^4/4 \rightarrow 3$	
	8		↑( )( )				
	9		0				
97	0		4	C_4			
	1		)	$C_4\, T^4/4$			
	2		+				
	3		(				
	4		↑( )				
	5		0	T			
	6		a^x				
	7		5				
	8		÷	T^5			
	9		5				
98	0		x	$T^5/5$			
	1		↓( )				
	2		4			$T^5/5 \rightarrow 4$	
	3		↑( )( )				
	4		0				
	5		5	C_5			
	6		)	$C_5\, T^5/5$			
	7		=	h_A			
	8		↓( )				
	9		6			$h_A \rightarrow 6$	
99	0		↑( )				
	1		0	T			
	2		x				
	3		↑( )( )				
	4		1				
	5		1	D_1			
	6		+	$D_1\, T$			
	7		(				
	8		↑( )				
	9		1	$T^2/2$			

STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
1000	0		×				
	1		↑( )( )				
	2		1				
	3		2	D_2			
	4		)	$D_2 \; T^2/2$			
	5		−				
	6		(				
	7		↑( )				
	8		2	$T^3/3$			
	9		×				
1010	0		↑( )( )				
	1		1				
	2		3	D_3			
	3		)	$D_3 \; T^3/3$			
	4		+				
	5		(				
	6		↑( )				
	7		3	$T^4/4$			
	8		×				
	9		↑( )( )				
1020	0		1				
	1		4	D_4			
	2		)	$D_4 \; T^4/4$			
	3		−				
	4		(				
	5		↑( )				
	6		4	$T^5/5$			
	7		×				
	8		↑( )( )				
	9		1				
1030	0		5	D_5			
	1		)	$D_5 \; T^5/5$			
	2		×	h_G			
	3		↓( )				
	4		7			$h_G \rightarrow 7$	
	5		↑( )				
	6		5	f			
	7		+	$f \; h_G$			
	8		↑( )				
	9		6	h_A			
1040	0		÷	$h_A + f \; h_G$			
	1		(				
	2		1	1			
	3		+				
	4		↑( )				
	5		5	f			
	6		)	$1 + f$			
	7		=	h			
	8		↓( )				
	9		8			$h \rightarrow 8$	

STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
1050	0		RESUME	END S.R. h (+)			
	1	√‾	IND/SYMB	SUBROUTINE "RG/J" (√‾)		f in 5	
	2		√‾				
	3		↑( )				
	4		5	f			
	5		x				
	6		↑( )( )				
	7		0				
	8		7	b = .035648			
	9		+				
1060	0		↑( )( )				
	1		0				
	2		6	a = .034522			
	3		÷				
	4		(	S.R. RG/J			
	5		1	1 (√‾)			
	6		+				
	7		↑( )				
	8		5	f			
	9		)	1 + f			
1070	0		÷				
	1		↑( )( )				
	2		0				
	3		0	J/R			
	4		=	RG/J			
	5		↓( )( )				
	6		2				
	7		9			RG/J → 29	
	8		RESUME				
	9	↓( )	IND/SYMB	SUBROUTINE "PRINT I" [↓( )]			
1080	0		↓( )				
	1		↑( )( )				
	2		2				
	3		0	P_e/P_i			
	4		↑( )( )				
	5		3				
	6		6	P. I.			
	7	EC	177				P. I.
	8		PRINTA				P_e/P_i
	9		2				
1090	0		1	SET UP POINTER 21			
	1		↓( )( )	STR 37			
	2		3				
	3		7				
	4		↓( )				
	5		•				
	6	8	IND/SYMB	SYMBOL . ADDRESS 8			
	7		8				
	8		↑( )( )	RCL ACCORD. TO POINTER			
	9		IND/SYMB				

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STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
110	0		PRINT A				PRINT ACC. POINTER
	1		1	1			
	2		↑( )( )				
	3		+				
	4		3				
	5		7	ADD 1 TO POINTER, STR (E)			
	6		↓( )( )				
	7		3				
	8		7	NEW POINTER, STR (37)			
	9		↓( )				
111	0		•	SET UP NEW POINTER			
	1		−				
	2		3				
	3		0	NEW POINTER − 30			
	4		=				
	5		JUMP				
	6		=				
	7		IND/SYMB	TO SYMB. ADD. IF NEW POINTER = 30			
	8		9				
	9		JUMP				
112	0		IND/SYMB	TO SYMB. ADD IF NEW POINTER ≦ 29			
	1		8				
	2	9	IND/SYMB	SYMB. ADDRESS 9			
	3		9				
	4	EC	176	1 LINE OF DOTS			• • • •
	5		RESUME	END S.R. PRINT I [↓( )]			
	6	$e^x/10^x$	IND/SYMB	SUBROUTINE " $\bar{Y}$ "; ($e^x/10^x$)			
	7		$e^x/10^x$				
	8		↑( )( )				
	9		3				
113	0		2	T_e'			
	1		÷				
	2		↑( )( )				
	3		2				
	4		1	T_i			
	5		=	T_e'/T_i			
	6		ln/log	$\ln(T_e'/T_i)$			
	7		x				
	8		↑( )( )				
	9		2				
114	0		9	R_G/J			
	1		CHSGN	$-R_G/J$			
	2		÷	$-(R_G/J)\ln(T_e'/T_i)$			
	3		(				
	4		↑( )( )				
	5		3				
	6		1	φ_e'			
	7		−				
	8		↑( )( )				
	9		3				

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STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
115	0		0	φ_i			
	1		)	$\varphi_e' - \varphi_i$			
	2		+				
	3		1				
	4		=	$1 - \frac{R_G}{J}\frac{\ln(T_e'/T_i)}{\varphi_e' - \varphi_i}$			
	5		1/x	$\bar{\gamma}$			
	6		↓( )( )				
	7		2				
	8		8			$\bar{\gamma} \rightarrow 28$	
	9		↑( )( )				
116	0		1				
	1		0	J			
	2		↓( )( )				
	3		X				
	4		2				
	5		9	$R_G/J \rightarrow R_G$		$R_G \rightarrow 29$	
	6		RESUME	END S.R. $\bar{\gamma}(c^x/10^x)$			
	7	÷	IND/SYMB	SUBROUTINE "COMPRESSOR" (÷)		$P_e/P_i \rightarrow 20$	
	8		÷			$T_i \rightarrow 21$ $\eta_c \rightarrow 23$	
	9		0	$f=0$		P.I. → 36	
117	0		↓( )				
	1		5			$f=0 \rightarrow 5$	
	2		↓( )( )				
	3		2				
	4		7			$f=0 \rightarrow 27$	
	5		↑( )( )				
	6		2				
	7		1	T_i			
	8		↓( )				
	9		0			$T_i \rightarrow 0$	
118	0		BRANCH	TO S.R. "h_i" (+) For $h_i = f(T_i)$			
	1		IND/SYMB				
	2		+	h_i			
	3		↓( )( )				
	4		2				
	5		2			$h_i \rightarrow 22$	
	6		BRANCH	TO S.R. "φ" (−) For $\varphi_i = f(T_i)$			
	7		IND/SYMB				
	8		−	φ_i			
	9		↓( )( )				
119	0		3				
	1		0			$\varphi_i \rightarrow 30$	
	2		BRANCH	TO S.R. "R_G/J" ($\sqrt{\ }$) for $f=0$			
	3		IND/SYMB				
	4		$\sqrt{\ }$	R_G/J			
	5		X				
	6		(				
	7		↑( )( )				
	8		2				
	9		0	P_e/P_i			

STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
120	0		ln/log	ln (Pe/Pi)			
	1		)				
	2		+	(RG/J) ln (Pe/Pi)			
	3		↑( )( )				
	4		3				
	5		0	φ_i			
	6		=	φ_e'			
	7		↓( )( )				
	8		3				
	9		1			$\varphi_e' \to 31$	
121	0	4	IND/SYMB	SYMBOL ADDRESS 4			
	1		4				
	2		HALT	ENTER: $T^* = Te'$ FOR ITERATION IN φ_e'	$T^* = Te'$		
	3		↓( )( )				
	4		3				
	5		2	$T^* = Te'$		$Te' \to 32$	
	6		↓( )				
	7		0			$T^* \to 0$	
	8		BRANCH	TO S.R. "φ" (−) FOR $\varphi^* = f(T^*, f=0)$			
	9		IND/SYMB				
122	0		−	φ^*			
	1		−				
	2		↑( )( )				
	3		3				
	4		1	φ_e'			
	5		=	$\varphi^* - \varphi_e' = \Delta\varphi$			
	6		2				
	7		0				
	8		•	P.I. 20.			
	9	EC	177				20.
123	0		PRINT A				$\Delta\varphi$
	1		↑( )				
	2		0	T^*			
	3		PRINT A				T^*
	4		HALT	IF $\Delta\varphi \cong 0$: ENTER: 0			
	5		JUMP				
	6		=	GO TO S.A. 5 ; IF $\Delta\varphi = 0$			
	7		IND/SYMB				
	8		5				
	9		JUMP	GO TO S.A. 4 IF $\Delta\varphi \neq 0$ FOR			
124	0		IND/SYMB	IMPROVED $T^* = Te'$			
	1		4				
	2	5	IND/SYMB	SYMBOL ADDRESS 5			
	3		5				
	4		↑( )( )				
	5		3	Unnecessary!			
	6		2	Te'			
	7		BRANCH	GO TO S.R. "h"; FOR $h_e' = f(Te', f=0)$			
	8		IND/SYMB				
	9		+	h_e'			

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STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
125	0		−				
	1		↑( )( )				
	2		2				
	3		2	h_i			
	4		÷				
	5		↑( )( )				
	6		2				
	7		3	η_c			
	8		+	$h_e - h_i$			
	9		↓( )( )				
126	0		2				
	1		6			$h_e - h_i \rightarrow 26$	
	2		↑( )( )				
	3		2				
	4		2				
	5		=	h_e			
	6		↓( )( )				
	7		2				
	8		5			$h_e \rightarrow 25$	
	9	6	IND/SYMB	SYMBOL. ADDRESS 6			
127	0		6				
	1		HALT	ENTER: $T^* = T_e$ FOR ITERATION FOR h_e	$T^* = T_e$		
	2		↓( )( )				
	3		2				
	4		4	$T^* = T_e$		$T_e \rightarrow 24$	
	5		↓( )				
	6		0			$T^* \rightarrow 0$	
	7		BRANCH	TO S.R "h" (+); FOR $h^* = F(T^*, f=0)$			
	8		IND/SYMB				
	9		+	h^*			
128	0		−				
	1		↑( )( )				
	2		2				
	3		5	h_e			
	4		=	$h^* - h_e = \Delta h$			
	5		2				
	6		1	P.I. 21			
	7		.				
	8	EC	177				21.
	9		PRINT A				Δh
129	0		↑( )				
	1		0	T^*			
	2		PRINT A				T^*
	3		HALT	IF $\Delta h \cong 0$: ENTER: 0			
	4		JUMP				
	5		=	GO TO S.A. 7 IF $\Delta h = 0$			
	6		IND/SYMB				
	7		7				
	8		JUMP	GO TO S.A. 6 IF $\Delta h \neq 0$ FOR			
	9		IND/SYMB	IMPROVED $T^* = T_e$			

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STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
130	0		6	↓ GO TO S.A. 6 FOR IMPROVED $T^* = T_e$			
	1	7	IND/SYMB	↑ SYMBOL ADDRESS 7			
	2		7	↓			
	3		BRANCH	↑ TO S.R. " $\bar{\gamma}$ " $(e^x/10^x)$			
	4		IND/SYMB			$\bar{\gamma} \rightarrow 28$	
	5		$e^x/10^x$	↓		$R_a \rightarrow 29$	
	6		BRANCH	↑ TO S.R. "PRINT I"			
	7		IND/SYMB				
	8		↓( )	↓			COMPR DATA
	9		JUMP	↑			
131	0		FLAG 1	IF FLAG 1 IS SET JUMP TO EC 040			
	1		IND/SYMB	(LOW COMP)			
	2	EC	040				
	3		JUMP	IF FLAG 1 IS NOT SET JUMP TO EC 041			
	4		IND/SYMB	(HIGH COMP)			
	5	EC	041	↓ END S.R. COMPR.			
	6	X	IND/SYMB	↑ SUBROUTINE "EXPANSION" (X)		$P_e/P_i \rightarrow 20$ $T_i \rightarrow 21$ $\eta_e \rightarrow 23$ $f \rightarrow 27$ P.J. → 36	
	7		X	↓			
	8		↑( )( )				
	9		2				
132	0		7	f			
	1		↓( )				
	2		5			$f \rightarrow 5$	
	3		BRANCH	↑ TO S.R. " R_G/J "			
	4		IND/SYMB				
	5		$\sqrt{\ }$	↓		$R_G/J \rightarrow 29$	
	6		↑( )( )				
	7		2				
	8		1	T_i			
	9		↓( )				
133	0		0			$T_i \rightarrow 0$	
	1		BRANCH	↑ TO S.R. " h " FOR $h_i = F(T_i, f)$			
	2		IND/SYMB				
	3		+	↓ h_i			
	4		↓( )( )				
	5		2				
	6		2			$h_i \rightarrow 22$	
	7		BRANCH	↑ TO S.R. " φ " FOR $\varphi_i = F(T_i, f)$			
	8		IND/SYMB				
	9		—	↓ φ_i			
134	0		↓( )( )				
	1		3				
	2		0			$\varphi_i \rightarrow 30$	
	3		+	φ_i			
	4		(				
	5		↑( )( )				
	6		2				
	7		0	P_e/P_i			
	8		ln/log	$\ln(P_e/P_i)$			
	9		X				

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STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
135	0		↑( )( )				
	1		2				
	2		9	R_G/J			
	3		)	$(R_G/J)\ln(P_e/P_i)$			
	4		=	φ_e'			
	5		↓( )( )				
	6		3				
	7		1			$\varphi_e' \to 31$	
	8	(	IND/SYMB	SYMBOL. ADDRESS (			
	9		(				
136	0		HALT	ENTER: $T^* = T_e'$ FOR ITERATION IN φ_e'	$T^* = T_e'$		
	1		↓( )( )				
	2		3				
	3		2			$T_e' \to 32$	
	4		↓( )				
	5		0			$T^* \to 0$	
	6		BRANCH	TO S.R. "φ" FOR $\varphi^* = F(T^*, f)$			
	7		IND/SYMB				
	8		−	φ^*			
	9		−				
137	0		↑( )( )				
	1		3				
	2		1	φ_e'			
	3		=	$\varphi^* - \varphi_e' = \Delta\varphi$			
	4		3				
	5		0	P. I. 30			
	6		•				
	7	EC	177				30.
	8		PRINT A				$\Delta\varphi$
	9		↑( )				
138	0		0	T^*			
	1		PRINT A				T^*
	2		HALT	IF $\Delta\varphi \cong 0$: ENTER : 0			
	3		JUMP				
	4		=	GO TO S.A.) IF $\Delta\varphi = 0$			
	5		IND/SYMB				
	6		)				
	7		JUMP	GO TO S.A. (IF $\Delta\varphi \neq 0$ FOR			
	8		IND/SYMB	IMPROVED $T^* = T_e'$			
	9		(				
139	0	)	IND/SYMB	SYMBOL. ADDRESS)			
	1		)				
	2		BRANCH	TO S.R. "h" FOR $h_e' = F(T_e', f)$			
	3		IND/SYMB				
	4		+	h_e'			
	5		CHSGN	$-h_e'$			
	6		+				
	7		↑( )( )				
	8		2				
	9		2	h_i			

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STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
140	0		×	$h_i - h_e'$			
	1		↑( )( )				
	2		2				
	3		3	η_e			
	4		−	$(h_i - h_e')\eta_e = h_i - h_e$			
	5		↓( )( )				
	6		2				
	7		6			$h_i - h_e \rightarrow 26$	
	8		↑( )( )				
	9		2				
141	0		2	h_i			
	1		=	$-h_e$			
	2		CHSGN	h_e			
	3		↓( )( )				
	4		2				
	5		5			$h_e \rightarrow 25$	
	6	⮥	IND/SYMB	SYMBOL. ADDRESS ⮥			
	7		⮥				
	8		HALT	ENTER: $T^* = T_e$ FOR ITERATION IN h_e	$T^* = T_e$		
	9		↓( )( )				
142	0		2				
	1		4			$T_e \rightarrow 24$	
	2		↓( )				
	3		0			$T^* \rightarrow 0$	
	4		BRANCH	TO S.R. "h" FOR $h^* = F(T^*, f)$			
	5		IND/SYMB				
	6		+	h^*			
	7		−				
	8		↑( )( )				
	9		2				
143	0		5	h_e			
	1		=	$h^* - h_e = \Delta h$			
	2		3				
	3		1	P.I. 31.			
	4		•				
	5	EC	177				31.
	6		PRINT A				Δh
	7		↑( )				
	8		0	T^*			
	9		PRINT A				T^*
144	0		HALT	IF $\Delta h \cong 0$: ENTER: 0			
	1		JUMP				
	2		=	IF. $\Delta h = 0$ GO TO S.A. ⩝			
	3		IND/SYMB				
	4		⩝				
	5		JUMP	GO TO S.A. ⮥ IF $\Delta h \neq 0$ FOR			
	6		IND/SYMB	IMPROVED $T^* = T_e$			
	7		⮥				
	8	⩝	IND/SYMB	SYMBOL. ADDRESS ⩝			
	9		⩝				

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STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
145	0		BRANCH	TO S.R. " $\bar{\gamma}$ "			
	1		IND/SYMB			$\bar{\gamma} \rightarrow 28$	
	2		$e^x/10^x$			$R_G \rightarrow 29$	
	3		BRANCH	TO S.R. " $(\gamma_\ell)_e, a_e$ "			
	4		IND/SYMB			$(\gamma_\ell)_e \rightarrow 33$	
	5		ln/LOG			$a_e \rightarrow 35$	
	6		↑( )( )				
	7		2				
	8		6	$h_i - h_e$			
	9		x				
146	0		↑( )( )				
	1		1				
	2		8	$2gJ$			
	3		=	$V_d^2 = 2gJ(h_i - h_e)$			
	4		√	V_d			
	5		↓( )( )				
	6		3				
	7		4			$V_d \rightarrow 34$	
	8		÷				
	9		↑( )( )				
147	0		3				
	1		5	a_e			
	2		=	$M_d = V_d / a_e$			
	3		↓( )( )				
	4		3				
	5		5			$M_d \rightarrow 35$	
	6		BRANCH				
	7		IND/SYMB	TO S.R. "PRINT I"			
	8		↓( )				DATA
	9		JUMP				
148	0		FLAG	IF FLAG 1 IS SET JUMP TO EC 044			
	1		IND/SYMB	(LOW TURBINE)			
	2	EC	044				
	3		JUMP				
	4		IND/SYMB	IF FLAG 1 IS NOT SET JUMP TO EC 046			
	5	EC	046	(JET NOZZLE)	END S.R. "EXPANSION"		
	6	ln/LOG	IND/SYMB	SUBROUTINE " $(\gamma_\ell)_e, a_e$ "; (ln/LOG)			
	7		ln/LOG	USE AFTER S.R. " $\bar{\gamma}$ "; ($e^x/10^x$)			
	8		↑( )( )				
	9		2				
149	0		4	T_e			
	1		÷				
	2		↑( )( )				
	3		2				
	4		5	h_e			
	5		x				
	6		↑( )( )				
	7		2				
	8		9	R_G			
	9		÷				

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STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
1500		↑( )( )				
1		1				
2		0	J			
3		CHSGN	−J			
4		+				
5		1	1			
6		=	$1-(R_G/J)\,T_e/h_e$			
7		1/x	$(\gamma_e)_e$			
8		↓( )( )				
9		3				
1510		3			$(\gamma_e)_e \rightarrow 33$	
1		x				
2		↑( )( )				
3		1				
4		6	g			
5		x				
6		↑( )( )				
7		2				
8		9	R_G			
9		x				
1520		↑( )( )				
1		2				
2		4	T_e			
3		=	$(\gamma_e)_e \; g \; R_G \; T_e = a_e^2$			
4		√	a_e			
5		↓( )( )				
6		3				
7		5			$a_e \rightarrow 35$	
8		RESUME	END S.R. "$(\gamma_e)_e, a_e$"			
9	π/e	IND/SYMB	SUBROUTINE ".HT" (π/e)		$\Delta h = h_i - h_e \rightarrow 26$	
1530		π/e			$T_i \rightarrow 21$ $\eta \rightarrow 23$	
1		↑( )( )			$f \rightarrow 27$	
2		2			P.I → 36	
3		1	T_i			
4		↓( )				
5		0			$T_i \rightarrow 0$	
6		↑( )( )				
7		2				
8		7	f			
9		↓( )				
1540		5			$f \rightarrow 5$	
1		BRANCH	TO S.R. "R_G/J" (√)			
2		IND/SYMB				
3		√			$R_G/J \rightarrow 29$	
4		BRANCH	TO S.R. "φ" (−) FOR $\varphi_i = F(T_i, f)$			
5		IND/SYMB				
6		—	φ_i			
7		↓( )( )				
8		3				
9		0			$\varphi_i \rightarrow 30$	

STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
155	0		BRANCH				
	1		IND/SYMB	TO S.R. "h"(+) FOR $h_i = F(T_i, f)$			
	2		+	h_i			
	3		↓( )( )				
	4		2				
	5		2			$h_i \rightarrow 22$	
	6		−				
	7		↑( )( )				
	8		2				
	9		6	$\Delta h = h_i - h_e$			
156	0		=	h_e			
	1		↓( )( )				
	2		2				
	3		5			$h_e \rightarrow 25$	
	4	2NDFUNC	IND/SYMB	SYMBOL. ADDRESS 2NDFUNC			
	5		2NDFUNC				
	6		HALT	ENTER: $T^* = T_e$ FOR ITERATION IN h_e	$T^* = T_e$		
	7		↓( )( )				
	8		2				
	9		4			$T_e \rightarrow 24$	
157	0		↓( )( )				
	1		3				
	2		2			$T_e \rightarrow 32$	
	3		↓( )				
	4		0			$T^* \rightarrow 0$	
	5		BRANCH				
	6		IND/SYMB	TO S.R. "h" (+) FOR $h^* = F(T^*, f)$			
	7		+	h^*			
	8		−				
	9		↑( )( )				
158	0		2				
	1		5	h_e			
	2		=	$\Delta h = h^* - h_e$			
	3		4				
	4		0	P.I. 40.			
	5		.				
	6	EC	177				40.
	7		PRINT A				Δh
	8		↑( )				
	9		0	T^*			
159	0		PRINT A				T^*
	1		HALT	IF $\Delta h \cong 0$: ENTER: 0			
	2		JUMP				
	3		=	IF $\Delta h = 0$ GO TO S.A. 1/x			
	4		IND/SYMB				
	5		1/x				
	6		JUMP	IF $\Delta h \neq 0$ GO TO S.A. 2NDFUNC			
	7		IND/SYMB	FOR IMPROVED $T^* = T_e$			
	8		2NDFUNC				
	9	1/x	IND/SYMB	SYMBOL. ADDRESS 1/x			

STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
160	0		1/x				
	1		↑( )( )				
	2		2				
	3		6	$h_i - h_e$			
	4		÷				
	5		↑( )( )				
	6		2				
	7		3	η			
	8		CHSGN	$-\eta$			
	9		+	$-(h_i - h_e)/\eta$			
161	0		↑( )( )				
	1		2				
	2		2	h_i			
	3		−	$h_e' = h_i - (h_i - h_e)/\eta$			
	4		↓( )( )				
	5		3				
	6		4			$h_e' \to 34$	
	7		↑( )( )				
	8		2				
	9		5	h_e			
162	0		=	$h_e' - h_e$			
	1		JUMP				
	2		=	IF $h_e' = h_e$ JUMP TO S.A. R →°			
	3		IND/SYMB				
	4		R →°				
	5	SIN/COS	IND/SYMB	SYMBOL. ADDRESS SIN/COS			
	6		SIN/COS				
	7		HALT	ENTER: $T^* = T_e'$ FOR ITERATION IN h_e'	$T^* = T_e'$		
	8		↓( )( )				
	9		3				
163	0		2			$T_e' \to 32$	
	1		↓( )				
	2		0			$T^* \to 0$	
	3		BRANCH	TO SUB.R. " h " (+) FOR $h^* = F(T^*, f)$			
	4		IND/SYMB				
	5		+	h^*			
	6		−				
	7		↑( )( )				
	8		3				
	9		4	h_e'			
164	0		=	$\Delta h = h^* - h_e'$			
	1		4				
	2		1	P.I. 41.			
	3		.				
	4	EC	177				41.
	5		PRINTA				Δh
	6		↑( )				
	7		0	T^*			
	8		PRINT A				T^*
	9		HALT	IF $\Delta h \cong 0$: ENTER: 0			

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STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
165	0		JUMP				
	1		=	IF $\Delta h = 0$ GO TO S.A. R→°			
	2		IND/SYMB				
	3		R→°				
	4		JUMP	IF $\Delta h \neq 0$ GO TO S.A. SIN/COS FOR			
	5		IND/SYMB	IMPROVED $T^* = T_e'$			
	6		SIN/COS				
	7	R→°	IND/SYMB	SYMBOL. ADDRESS R→°			
	8		R→°				
	9		BRANCH	TO S.R. "φ" (−) FOR $\varphi_e' = F(T_e', f)$			
166	0		IND/SYMB				
	1		−	φ_e'.			
	2		↓( )( )				
	3		3				
	4		1	φ_e'		$\varphi_e' \to 31$	
	5		−				
	6		↑( )( )				
	7		3				
	8		0	φ_i			
	9		÷	$\varphi_e' - \varphi_i$			
167	0		↑( )( )				
	1		2				
	2		9	R_G/J			
	3		=	$(\varphi_e' - \varphi_i)/(R_G/J)$			
	4		$e^x/10^x$	$P_e/P_i = e^{(\varphi_e' - \varphi_i)/(R_G/J)}$			
	5		↓( )( )				
	6		2				
	7		0			$P_e/P_i \to 20$	
	8		BRANCH	TO S.R. "$\bar{\gamma}$" ($e^x/10^x$)			
	9		IND/SYMB			$\bar{\gamma} \to 28$	
168	0		$e^x/10^x$			$R_a \to 29$	
	1		BRANCH	TO S.R. "$(\gamma_t)_e$, a_e" (ln/LOG)			
	2		IND/SYMB			$(\gamma_t)_e \to 33$	
	3		ln/LOG			$a_e \to 35$	
	4		BRANCH	TO S.R. "PRINT I" [↓( )]			
	5		IND/SYMB				
	6		↓( )				DATA
	7		JUMP	IF FLAG 1 IS SET JUMP TO EC 042			
	8		FLAG	(HIGH TURBINE)			
	9		IND/SYMB				
169	0		EC 042				
	1		JUMP	IF FLAG 1 IS NOT SET JUMP TO EC 047			
	2		IND/SYMB	(INLET DUCT			
	3		EC 047	(END S.R. "HT")			
	4	↑( )	IND/SYMB	SUBROUTINE "PRINT II" [↑( )]			
	5		↑( )				
	6		↑( )( )				
	7		2				
	8		5	Te			
	9		↑( )( )				

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STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
1700	0		2				
	1		9	RCL P.I.			
	2	EC	177				P.I.
	3		PRINT A				T_e
	4		↑( )( )				
	5		2				
	6		6	h_e			
	7		PRINT A				h_e
	8		↑( )( )				
	9		2				
1710	0		7	Δf or $\zeta = \dot{w}_{ii}/\dot{w}_i$			
	1		PRINT A				Δf or ζ
	2		↑( )( )				
	3		2	S.R. "PRINT II"			
	4		8	f_e [↑( )]			
	5		PRINT A				f_e
	6	EC	176	1 LINE OF DOTS			. . . .
	7		RESUME				
	8	a^x	IND/SYMB	SUBROUTINE "BURNER" (a^x)		$T_i \rightarrow 20$ $f_i \rightarrow 21$ $T_e \rightarrow 25$	
	9		a^x				
1720	0		↑( )( )			$\eta_0 \rightarrow 22$ P.I $\rightarrow 29$	
	1		2				
	2		0	T_i			
	3		↓( )				
	4		0			$T_i \rightarrow 0$	
	5		BRANCH	TO S.R. "h"(+) FOR $(h_A)_i = F(T_i)$			
	6		IND/SYMB	$(h_G)_i = F(T_i)$			
	7		+				
	8		↑( )				
	9		6	$(h_A)_i$			
1730	0		↓( )( )				
	1		2				
	2		3			$(h_A)_i \rightarrow 23$	
	3		↑( )				
	4		7	$(h_G)_i$			
	5		↓( )( )				
	6		2				
	7		4			$(h_G)_i \rightarrow 24$	
	8		↑( )( )				
	9		2				
1740	0		5	T_e			
	1		↓( )				
	2		0			$T_e \rightarrow 0$	
	3		BRANCH	TO S.R. "h"(+) FOR $(h_A)_e = F(T_e)$			
	4		IND/SYMB	$(h_G)_e = F(T_e)$			
	5		+				
	6		↑( )				
	7		6	h_{Ae}			
	8		−				
	9		↑( )( )				

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STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
1750	0		2				
	1		3	h_{Ai}			
	2		+	$h_{Ae}-h_{Ai}$			
	3		(				
	4		↑( )( )				
	5		2				
	6		1	f_i			
	7		x				
	8		(				
	9		↑( )				
1760	0		7	h_{Ge}			
	1		−				
	2		↑( )( )				
	3		2				
	4		4	h_{Gi}			
	5		)	$h_{Ge}-h_{Gi}$			
	6		)	$f_i(h_{Ge}-h_{Gi})$			
	7		÷				
	8		(				
	9		↑( )( )				
1770	0		0				
	1		9	h_f			
	2		+				
	3		(				
	4		↑( )( )				
	5		2				
	6		2	η_B			
	7		x				
	8		↑( )( )				
	9		0				
1780	0		8	LHV			
	1		)				
	2		−				
	3		↑( )				
	4		7	h_{Ge}			
	5		)	$h_f + \eta_B \text{LHV} - h_{Ge}$			
	6		+	Δf			
	7		↓( )( )				
	8		2				
	9		7			$\Delta f \rightarrow 27$	
1790	0		↑( )( )				
	1		2				
	2		1	f_i			
	3		x	$f_e = \Delta f + f_i$			
	4		↓( )( )				
	5		2				
	6		8			$f_e \rightarrow 28$	
	7		↑( )				
	8		7	h_{Ge}			
	9		+	$f_e\ h_{Ge}$			

STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
180	0		↑( )				
	1		6	h_{Ae}			
	2		÷	$h_{Ae} + f_e h_{ge}$			
	3		(				
	4		1	1			
	5		+				
	6		↑( )( )				
	7		2				
	8		8	f_e			
	9		)	$1 + f_e$			
181	0		=	h_e			
	1		↓( )( )				
	2		2				
	3		6			$h_e \to 26$	
	4		BRANCH	TO S.R. "PRINT II" [↑( )]			DATA
	5		IND/SYMB				
	6		↑( )				
	7		RESUME	END S.R. "BURNER"(a*)			
	8	Φ	IND/SYMB	SUBROUTINE "MIXING" (Φ)		$T_i \to 20$ $f_i \to 21$	
	9		Φ			$T_{ii} \to 22$	
182	0		↑( )( )			$f_{ii} \to 23$ $\varphi \to 27$	
	1		2			PI → 29	
	2		0	T_i			
	3		↓( )				
	4		0			$T_i \to 0$	
	5		↑( )( )				
	6		2				
	7		1	f_i			
	8		↓( )				
	9		5			$f_i \to 5$	
183	0		BRANCH	TO S.R. "h" FOR $h_i = F(T_i, f_i)$			
	1		IND/SYMB				
	2		+	h_i			
	3		x				
	4		(				
	5		1				
	6		+				
	7		↑( )( )				
	8		2				
	9		1	f_i			
184	0		)	$1 + f_i$			
	1		=	$(1 + f_i) h_i$			
	2		↓( )( )				
	3		2				
	4		4			$(1+f_i)h_i \to 24$	
	5		↑( )( )				
	6		2				
	7		2	T_{ii}			
	8		↓( )				
	9		0			$T_{ii} \to 0$	

STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
185	0		↑( )( )				
	1		2				
	2		3	f_{ii}			
	3		↓( )				
	4		5			$f_{ii} \to 5$	
	5		BRANCH	TO S.R. "h" FOR $h_{ii} = F(T_{ii}; f_{ii})$			
	6		IND/SYMB				
	7		+	h_{ii}			
	8		x				
	9		↑( )( )				
186	0		2				
	1		7	ζ			
	2		x	ζh_{ii}			
	3		(				
	4		1	1			
	5		+				
	6		↑( )( )				
	7		2				
	8		3	f_{ii}			
	9		)	$1+f_{ii}$			
187	0		+	$\zeta h_{ii}(1+f_{ii})$			
	1		↑( )( )				
	2		2				
	3		4	$(1+f_i)h_i$			
	4		÷	$(1+f_i)h_i + \zeta h_{ii}(1+f_{ii})$			
	5		(				
	6		1	1			
	7		+				
	8		↑( )( )				
	9		2				
188	0		7	ζ			
	1		+	$1+\zeta$			
	2		↓( )				
	3		6			$1+\zeta \to 6$	
	4		(				
	5		↑( )( )				
	6		2				
	7		7	ζ			
	8		x				
	9		↑( )( )				
189	0		2				
	1		3	f_{ii}			
	2		+	ζf_{ii}			
	3		↑( )( )				
	4		2				
	5		1	f_i			
	6		)	$f_i + \zeta f_{ii}$			
	7		↓( )				
	8		7			$f_i+\zeta f_{ii} \to 7$	
	9		)	$1+\zeta+f_i+\zeta f_{ii}$			

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STEP		SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
190	0		=	h_e			
	1		↓( )( )				
	2		2				
	3		6			$h_e \to 26$	
	4		↑( )				
	5		7	$f_i + \zeta f_{ii}$			
	6		÷				
	7		↑( )				
	8		6	$1 + \zeta$			
	9		=	f_e			
191	0		↓( )( )				
	1		2				
	2		8			$f_e \to 28$	
	3		↓( )				
	4		5			$f_e \to 5$	
	5		↑( )( )				
	6		2				
	7		0	T_i			
	8		↓( )( )				
	9		2				
192	0		5	SET $T_e = T_i$ IF $T_i = T_{ii}$		$T_i = T_e \to 25$	
	1		−				
	2		↑( )( )				
	3		2				
	4		2	T_{ii}			
	5		=	$T_i - T_{ii}$			
	6		JUMP	TO S.A. Σ_0 IF $T_i = T_{ii}$			
	7		=	TO S.A. 1 IF $T_i \neq T_{ii}$			
	8		IND/SYMB				
	9		Σ_0				
193	0	1	IND/SYMB	SYMBOL. ADDRESS 1			
	1		1				
	2		HALT	ENTER: $T^* = T_e$ FOR ITERATION IN h_e	$T^* = T_e$		
	3		↓( )( )				
	4		2				
	5		5			$T_e \to 25$	
	6		↓( )				
	7		0			$T^* \to 0$	
	8		BRANCH	TO S.R. "h" FOR $h^* = F(T^*, f_e)$			
	9		IND/SYMB				
194	0		+	h^*			
	1		−				
	2		↑( )( )				
	3		2				
	4		6	h_e			
	5		=	$\Delta h = h^* - h_e$			
	6		1				
	7		0	P.I. 10.			
	8		•				
	9	EC	177				10.

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STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
1950		PRINT A				Δh
1		↑( )				
2		0	T^*			
3		PRINT A				T^*
4		HALT	IF $\Delta h \cong 0$: ENTER : 0			
5		JUMP				
6		=	IF $\Delta h = 0$ GO TO S.A. Σ_0			
7		IND/SYMB				
8		Σ_0				
9		JUMP	IF $\Delta h \neq 0$ GO TO S.A. 1 FOR			
1960		IND/SYMB	IMPROVED $T^* = T_e$			
1		1				
2	Σ_0	IND/SYMB	SYMBOL. ADDRESS Σ_0			
3		Σ_0				
4		BRANCH	TO S.R. "PRINT II"			DATA
5		IND/SYMB				
6		↑( )				
7		JUMP	IF FLAG1 IS SET JUMP to EC 043			
8		FLAG 1	(MIXING AFTER HT)			
9		IND/SYMB				
1970	EC	043				
1		JUMP	IF FLAG1 IS NOT SET JUMP TO			
2		IND/SYMB	S.A. EC 045 END	S.R. MIX	ING	
3	EC	045	(MIXING AFTER D.B. & A.B.) END	PROGRAM	514	
4						
5						
6						
7						
8						
9						
1980						
1						
2						
3						
4						
5						
6						
7						
8						
9						
0						
1						
2						
3						
4						
5						
6						
7						
8						
9						

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PROGRAM: VA 5 14 PAGE: SP1 OF 1 ; DATE: 6/73 ; BY: VA

SCRATCH PAD MEMORY STORAGE

0	1	2	3	4	
T	$T^2/2$	$T^3/3$	$T^4/4$		φ
T	$T^2/2$	$T^3/3$	$T^4/4$	$T^5/5$	h

5	6	7	8	9	
f	φ_A	φ			φ
f	h_A	h_G	h		h
	$1 + \varsigma$	$f_i + \varsigma f_{ii}$			Φ

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PROGRAM: VA 514 PAGE: S1 OF 3 DATE 6/73 BY: VA.

MAIN STORAGE BOOKKEEPING

REGISTER		CONTENTS 1	CONTENTS 2	CONTENTS 3
00	0	$J/R = 778.16/1545.43$		
	1	C_1		
	2	C_2		
	3	C_3 ENTERED		
	4	C_4 BY PROG.		
	5	C_5 VA 513		
	6	$a = .034522$		
	7	$b = .035648$		
	8	LHV = 18,400		
	9	h_f = 260		
10	0	J = 778.16		
	1	D_1		
	2	D_2		
	3	D_3		
	4	D_4		
	5	D_5		
	6	g = 32.174		
	7	J/550		
	8	2 g J		
	9			
20	0	P_e/P_i (INPUT)	P_e/P_i (INPUT)	P_e/P_i
	1	T_i (INPUT)	T_i (INPUT)	T_i (INPUT) PRINT-OUT
	2	h_i	h_i PRINT-OUT	h_i "PRINT I"
	3	η_c (INPUT) PRINT-OUT	η_e (INPUT) "PRINT I"	η (INPUT) ↓( )
	4	T_e "PRINT I"	T_e SUB.ROUT [↓( )]	T_e SUB.ROUT
	5	h_e [↓( )]	h_e "EXPANS"	h_e "HT"
	6	$h_e - h_i$	$h_i - h_e$ (X)	$h_i - h_e$ (INPUT) ($\bar{\gamma}$/e)
	7	f = 0 SUB.ROUT	f (INPUT)	f (INPUT)
	8	$\bar{\gamma}$ "COMPR"	$\bar{\gamma}$	$\bar{\gamma}$
	9	R_G/J | R_G | (÷)	R_G/J | R_G	R_G/J | R_G
30	0	φ_i	φ_i	φ_i
	1	φ_e'	φ_e'	φ_e'
	2	T_e'	T_e'	T_e'
	3		$(\gamma_c)_e$	$(\gamma_e)_e$
	4		V_d	h_e'
	5		a_e | M_d	a_e
	6	PRINT IDENTIF.	PRINT IDENT.	PRINT IDENT.
	7	POINTER	POINTER	POINTER
	8			
	9			
40	0	(SEE PAGE S 2)		
	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			

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PROGRAM: VA 514 PAGE: S2 OF 3 DATE 6/73 BY: VA

MAIN STORAGE BOOKKEEPING

REGISTER	CONTENTS 4 (20-29)	CONTENTS 5 (20-29)	CONTENTS 6 (20-29)
0			
1			
2			
3			
4			
5			
6			
7			
8			
9			
0			
1			
2			
3			
4			
5			
6			
7			
8			
9			
2 0	T_i (INPUT) ↑	T_i (INPUT) ↑	
1	f_i (INPUT)	f_i (INPUT)	
2	η_B (INPUT)	T_{ii} (INPUT)	
3	h_{Ai} SUBROUT	f_{ii} (INPUT) SUBROUT	
4	h_{Gi} "BURNER"	$h_i(1+f_i)$ "MIXING"	
5	T_e (INPUT) (a^x) ↑	T_e (Φ) ↑	I_{sp} ↑ " ↑ "
6	h_e PRINT-OUT	h_e PRINT-OUT "PRINT II"	SFC OVERALL PRINT II
7	Δf "PRINT II"	ζ (INPUT) [↑( )]	b PERFORM. [↑( )]
8	f_e ↓[↑( )]	f_e ↓	M_d ↓ ↓
9	PRINT IDENT. ↓	PRINT IDENT. ↓	PRINT IDENT. -200
0			
1			
2			
3			
4			
5			
6			
7			
8			
9	CONTENTS 1 (40-49)		
4 0	P_0 ↑		
1	T_0		
2	P_2/P_1 ENTERED		
3	P_3/P_1 BY PROG.		
4	T_4 VA 513		
5	$T_9 = T_{10}$		
6	ξ		
7	λ_I		
8	λ_{BP}		
9	λ_B		

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PROGRAM: VA 514 PAGE: S3 OF 3 DATE 6/73 BY: VA

MAIN STORAGE BOOKKEEPING

REGISTER		CONTENTS 1	CONTENTS 2	CONTENTS 3
5	0	$\lambda_{DB} = \lambda_{AB}$		
	1	η_{LC}		
	2	η_{HC}		
	3	η_{HT} ENTERED		
	4	η_{LT} BY PROG.		
	5	η_{B} VA 513		
	6	η_{AB}		
	7	Ψ_{N}		
	8			
	9	POINTER		
6	0	D_{T1}		
	1	r_{h1}		
	2	U_{T} INPUT		
	3	β_{1T}		
	4	k_1 PRINT-OUT		
	5	F		
	6	$\dot{W}$		
	7	HP_{LC}		
	8	HP_{HC}		
	9	$M_{W1} = W_1/a_1$		
7	0	$h_2 - h_1$		
	1	$h_3 - h_2$		
	2	T_3		
	3	f_B'		
	4	P_5 / P_4		
	5	T_5		
	6	P_8 / P_5		
	7	f_B		
	8	$h_6 - h_8$		
	9	b		
8	0	T_8		
	1	Δf_{AB}		
	2	$f_e = f_B + \Delta f_{AB}$		
	3	T_2		
	4	f_N		
	5	I_{SP}		
	6			
	7			
	8			
	9			
9	0	$\sin \beta_{1T}$		
	1	$U_T \cot \beta_{1T}$		
	2	$C = \pi/4 \, D_{T1}^2 (1 - r_{h1}^2) \, k_1$		
	3			
	4			
	5			
	6			
	7			
	8			
	9			

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Bypass Engine
After- and Duct Burning Engine
Real Gas Effects
Jet Engine Diameter for Specified Thrust

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A calculating procedure is presented for the sea-level static performance of duct burning and afterburning bypass jet engines that have a low pressure and a high pressure spool. Performance values can be determined also for operation without reheat. Influence of temperature and fuel/air ratio on the thermodynamic properties of air and combustion gases is taken into account. A calculating program for a Monroe 1880-43 programmable electronic desk calculator is described which makes it possible to evaluate effects of changes of parameters on performance with minimum effort. (continued)

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20.
The program will be used to establish the characteristics of compressors required for propulsive units of later generation Navy air-superiority fighter aircraft, to investigate whether the Turbo-Propulsion Laboratory of NPS would be capable of undertaking research and development work of such machines.

Programs of the type presented,and the use of modern programmable desk calculators, will also be of great value for instructional purposes. Teachers can then concentrate on the fundamental nature of particular topics and need not waste time on lengthy derivations, or on simplifications and approximations that are introduced only to solve equations with elementary means. The students would be relieved of the drudgery of routine hand calculations that do not contribute to a better understnading of the subject matter.